Appendix A

Evaluation of Hydrologic Conditions

Tables

Figures

A-1.0 INTRODUCTION

A-1.1 Overview

Major flooding occurred between May 13 and May 17, 2006, throughout much of central and southern New Hampshire. Record peak flood discharges were recorded at 14 stream gages that have at least 10 years of record. Peak discharges with recurrence intervals equal to or in excess of 50 years were observed at 14 stream gages; at 8 of these 14 stream gages the recurrence intervals exceeded 100 years (see Table A-1). Significant property damage, along with numerous road closures and evacuations of residential areas occurred as a result of this widespread flooding. The flood damage was severe and widespread enough to result in the issuance of a Presidential Major Disaster Declaration for seven New Hampshire Counties on May 25, 2006.

Less than one year later, from April 16–18, 2007, major flooding again occurred in central and southern New Hampshire. Record peak flood discharges were recorded at six stream gages that have at least 10 years of record; at three of these six gage sites, the previous record peak discharge had been set during the May 2006 flood. Peak flood discharges with recurrence intervals equal to or in excess of 50 years were recorded at 10 stream gages during this event; at 7 of these 10 stream gages the recurrence intervals exceeded 100 years (see Table A-1). This severe flood event resulted in significant property damage, along with numerous road closures and evacuations of residential areas. As a result of the severity and scope of flood-related damages caused by the April 2007 flood a Presidential Major Disaster Declaration was issued for five New Hampshire counties on April 27, 2007; a sixth County was added to the disaster Declaration on May 10, 2007.

As a result of these recent severe floods in New Hampshire the Federal Emergency Management Agency (FEMA), initiated an independent evaluation to characterize the meteorologic and hydrologic conditions prior to and during the May 2006 and the April 2007 flooding in New Hampshire and to compare and contrast the conditions associated with the two flood events. In addition, this study will provide recommendations for improving water management procedures and dam operations to reduce the impacts from future flooding. Numerical hydrologic and hydraulic models of the affected river basins were developed or adapted from existing models and used to evaluate the effects of various alternative procedures and policies. The results of the investigation will be presented in two parts: the initial characterization and description of the hydrologic and meteorologic conditions, and the description of the development and use of the hydrologic models to evaluate various scenarios.

The purpose of this appendix is to investigate and document the general meteorologic and hydrologic conditions in the affected areas of New Hampshire prior to and during the May 2006 and April 2007 flood events. The general hydrologic conditions considered include antecedent conditions, characteristics of the precipitation events that resulted in the flood events, and characteristics of the flood discharges. In addition, the general hydrologic conditions for the April 2007 and May 2006 flood events will compared and contrasted.

A-1.2 Effect of Antecedent Conditions on Flood Peaks

Stream flow, in general, can be thought of as being composed of two components: base flow and direct runoff. Base flow is the water that flows in a stream between rainfall or snowmelt events and consists primarily of water from shallow groundwater sources. Direct runoff is the water that flows over (or ‘runs off’ of) the surface of the land during and right after a rainfall event and is eventually collected in streams and rivers.

The base flow contribution to stream flow typically results from rainfall or snowmelt that soaks into the ground and then travels through porous shallow soil or fractured rock (depending on the specific geographic setting) to the stream. The time it takes for water to soak into the ground and then travel through the shallow soil or fractured rock is on the order of weeks and months and is dependent on the characteristics of the soil and fractured rock as well as the general topographic setting of the drainage area of the stream. This slow release of water from the water table sustains flow in streams during periods between rainfall events.

As noted above, direct runoff is the water from rainfall or snowmelt that flows over land or through small ditches directly into streams and rivers. The time it takes for direct runoff to reach a stream or river is on the order of hours and days and depends on the land cover, land use, and steepness of the land over which the runoff travels. This rapid contribution to stream flow leads to the rapid rises in streams during and after rainfall events and is the component of stream flow most responsible for flooding.

The amount of water from rainfall or snowmelt that becomes direct runoff and then contributes directly to stream flow, and in some cases flooding, is dependent on several factors. As discussed above, some portion of the rainfall or snowmelt soaks into the ground and reaches the stream weeks or months later as base flow, but does not contribute directly to stream flow during flood events. The amount of rainfall or snowmelt that is absorbed from a rainfall or snowmelt event depends for the most part on two factors: the types of land cover and land uses found in the drainage area and the ability and capacity of the soils in the drainage area to absorb water.

Although development and urban growth can change the land cover and land use characteristics of a drainage area with time, these changes are relatively gradual and typically confined to small areas relative to the total drainage area of a large stream. In contrast, the ability and capacity of soils to absorb water from rainfall or snowmelt can vary greatly depending on the moisture and temperature of the soil at the time of the rainfall or snowmelt. In general terms, the soil can be compared to a sponge that when saturated or full of water can no longer absorb additional water. As a result, if the general soil conditions are dry prior to a rainfall or snowmelt event, a larger portion of the total rainfall will be absorbed into the ground and a smaller amount will be available for direct runoff. Conversely, if general soil conditions are wet prior to a rainfall or snow melt event, then a smaller portion of the rainfall or snowmelt will be absorbed into the ground and a larger amount of the rainfall or snowmelt will contribute to direct runoff and the resultant stream flow amounts will be greater. In addition, if the ground is frozen, then the absorption capacity of the soil is greatly reduced and direct runoff is increased accordingly.

As such, differences in land cover and land use can and often do explain why similar amounts of rainfall or snowmelt can produce difference amounts of direct runoff on different stream or rivers. However, in many cases, storms with similar amounts of rainfall or snowmelt will result in significantly different amounts of direct runoff on the same stream or river. These differences in the direct runoff response for similar storms on a particular stream or river are the result of differences in the soil moisture and temperature conditions at the beginning of the rainfall or snowmelt event. Soil moisture and temperature conditions are a direct result of the rainfall and temperature conditions in the weeks and months leading up to a specific storm event. In general, the climatic and soil conditions leading up to specific storm events are referred to as antecedent conditions. Variations in the antecedent conditions for a given drainage basin explain the large variations that are observed in the relation between rainfall amount and peak stream flows for a given drainage basin.

A-1.3 Study Area

The study area for this investigation includes the areas in central and southern New Hampshire affected by the May 2006 and April 2007 flood events. This area includes the Cocheco, Contoocook, Isinglass, Lamprey, Oyster, Piscataquog, Salmon Falls, Soucook, Souhegan, and Suncook River basins. The Contoocook, Piscataquog, Soucook, Souhegan, and Suncook River basins are all tributary to the Merrimack River, while the Cocheco, Isinglass, Lamprey, Oyster, and Salmon Falls River basins are all part of the Piscataqua-Salmon Falls River basin, which drains directly to the Atlantic Ocean (see Figure A-1).

The river basins included in the study area drain all or parts of Belknap, Carroll, Cheshire, Hillsborough, Merrimack, Rockingham, Strafford, and Sullivan Counties. The terrain elevation in this part of New Hampshire ranges from sea level along the Atlantic Coast to more than 2,000 feet North American Vertical Datum of 1988 (NAVD 88) in the more mountainous areas in the north-central part of the study area. The climate in New Hampshire is generally humid, with an average annual precipitation of about 43 inches. The total precipitation is distributed fairly evenly across the State, except in areas of high elevation (above 4000 feet) which typically receive as much as 10 inches more than the average precipitation. In addition there is little seasonal variation in precipitation, with winter and spring months (December–May) receiving slightly less than half (46 percent) of the average annual precipitation.

The following table and figures show the streams and major tributaries and the towns in each of the ten study basins. The upper portions of most of the watersheds are relatively rural and highly forested with slightly increasing densities of population and urban land use in the downstream portions. The severity of storm events varied by basin and sometimes within basin depending on rainfall patterns and antecedent conditions.

Table A-1: Data for Individual Watersheds

Watershed Name	Tributary to:	Drainage Area (square miles)	Recurrence Interval for May 2006 Flood	Recurrence Interval for April 2007 Flood
Cocheco	Great Bay	111	50-100	10-50
Contoocook	Merrimack River	764	10-50	2-10
Isinglass	Great Bay	74	10-50	10-50
Lamprey	Great Bay	214	50-100	50-100
Oyster	Great Bay	31	10-50	100-500
Piscataquog	Merrimack River	217	10-50	10-50
Salmon Falls	Great Bay	188	10-50	10-50
Soucook	Merrimack River	91	100-500	10-50
Souhegan	Merrimack River	220	2-10	50-100
Suncook	Merrimack River	256	10-50	100-500

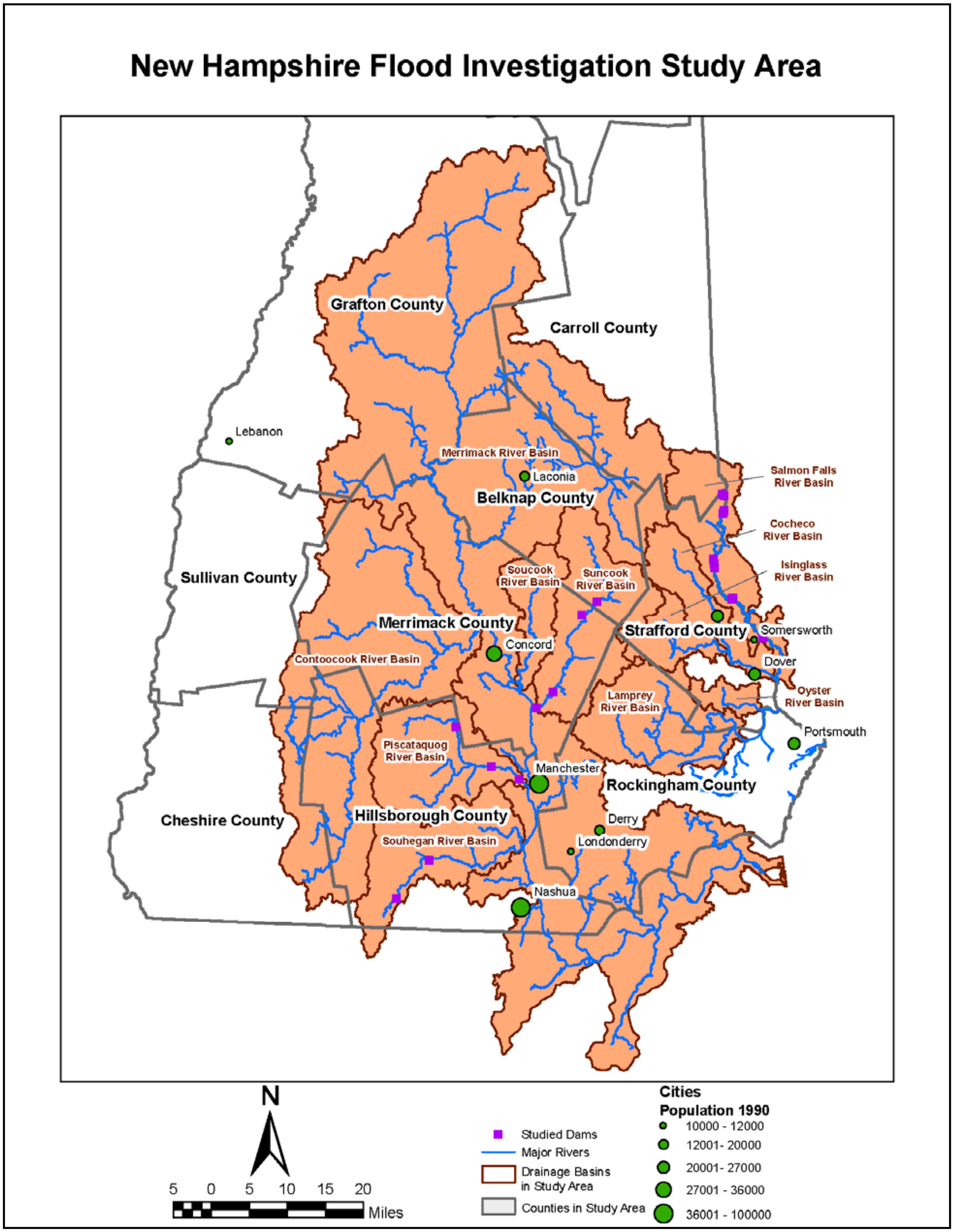

Figure A-1: New Hampshire Flood Investigation Study Area

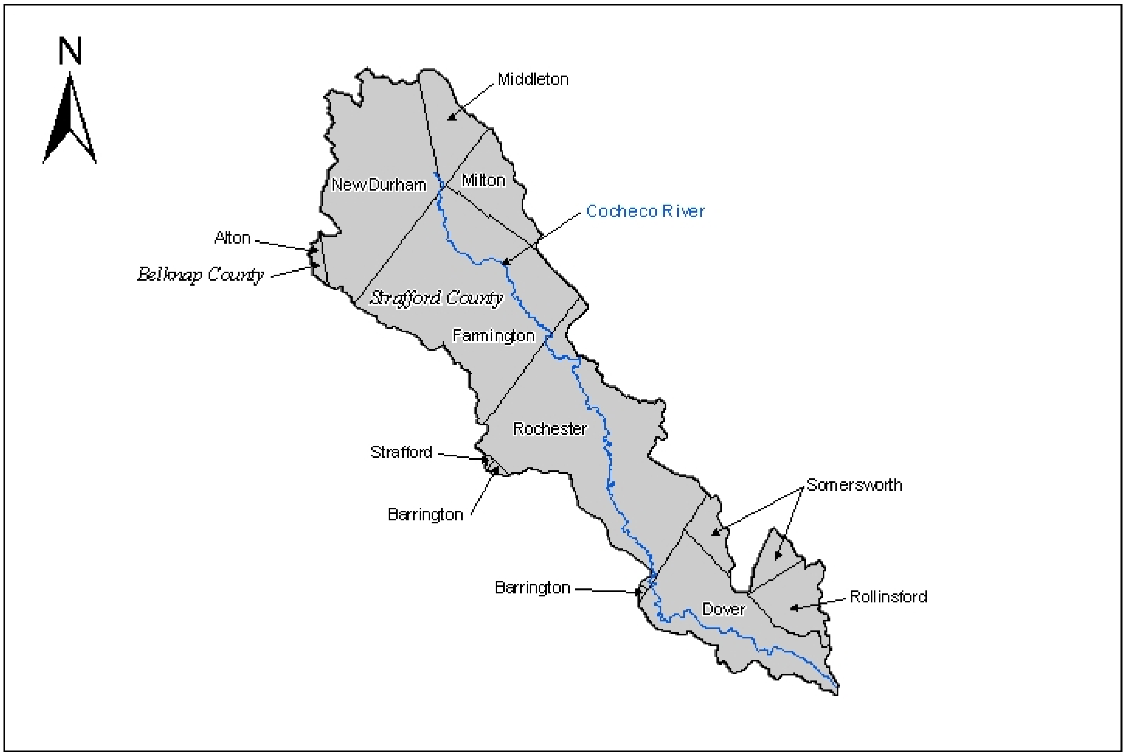

Figure A-1a: Cocheco River Watershed

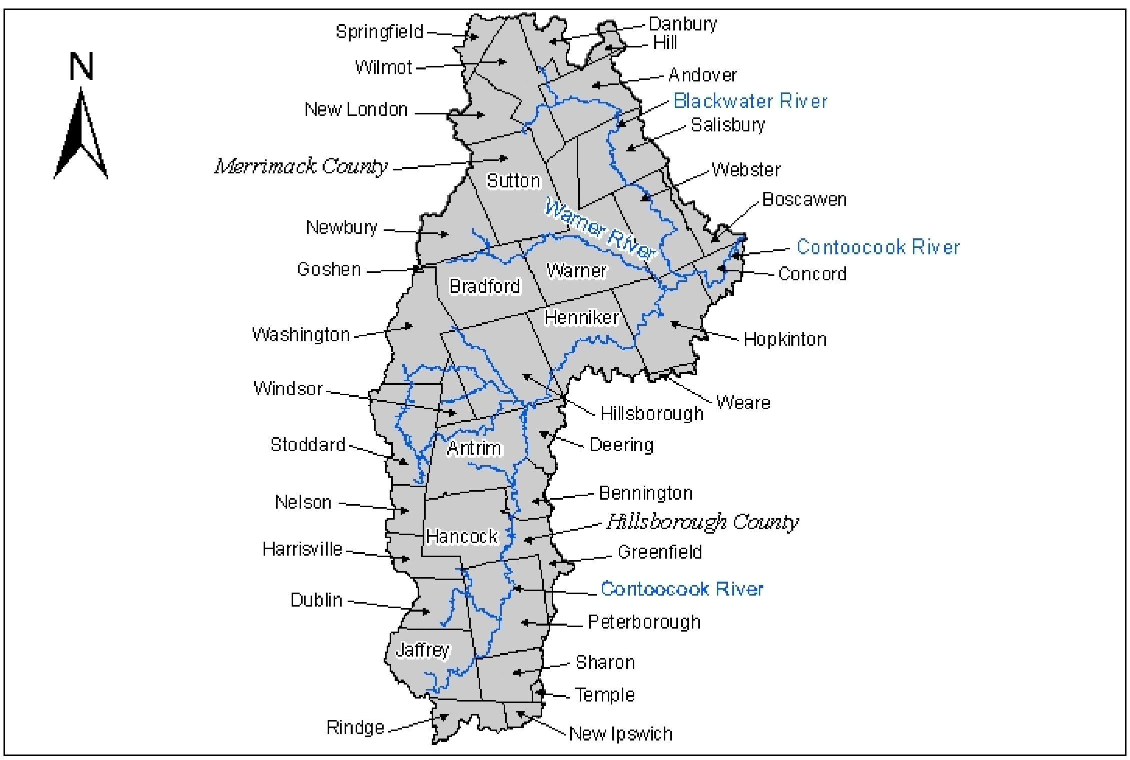

Figure A-1b: Contoocook River Watershed

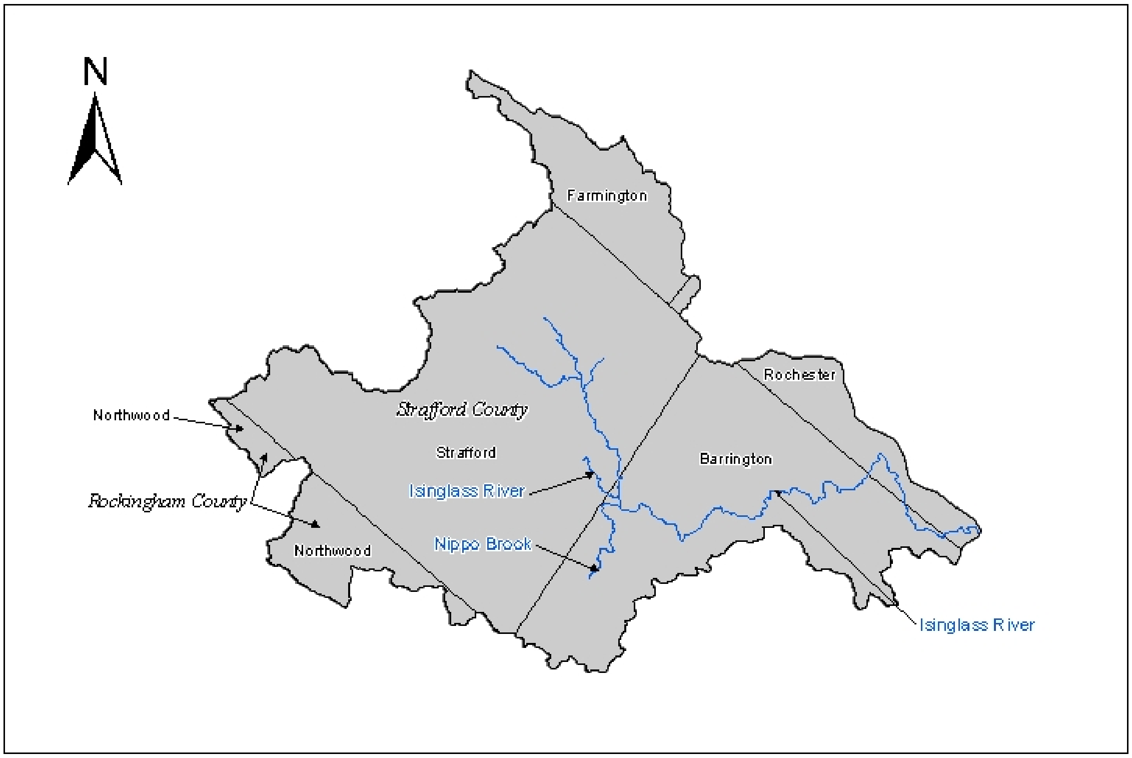

Figure A-1c: Isinglass River Watershed

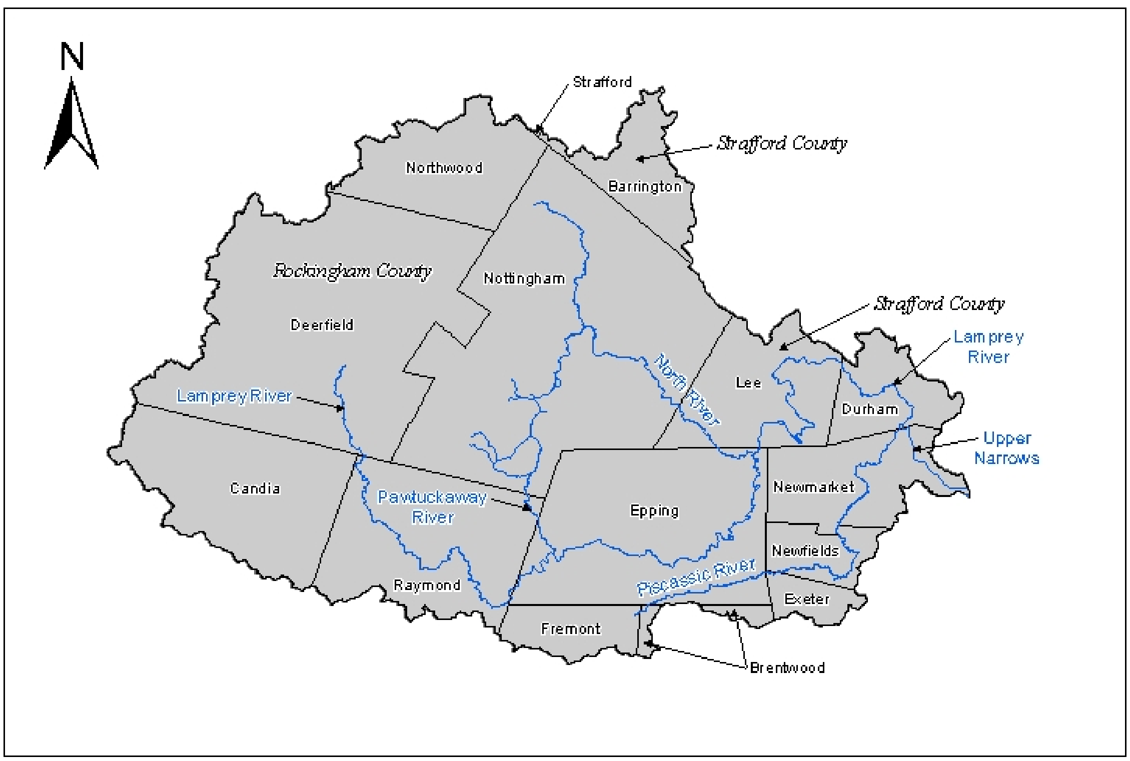

Figure A-1d: Lamprey River Watershed

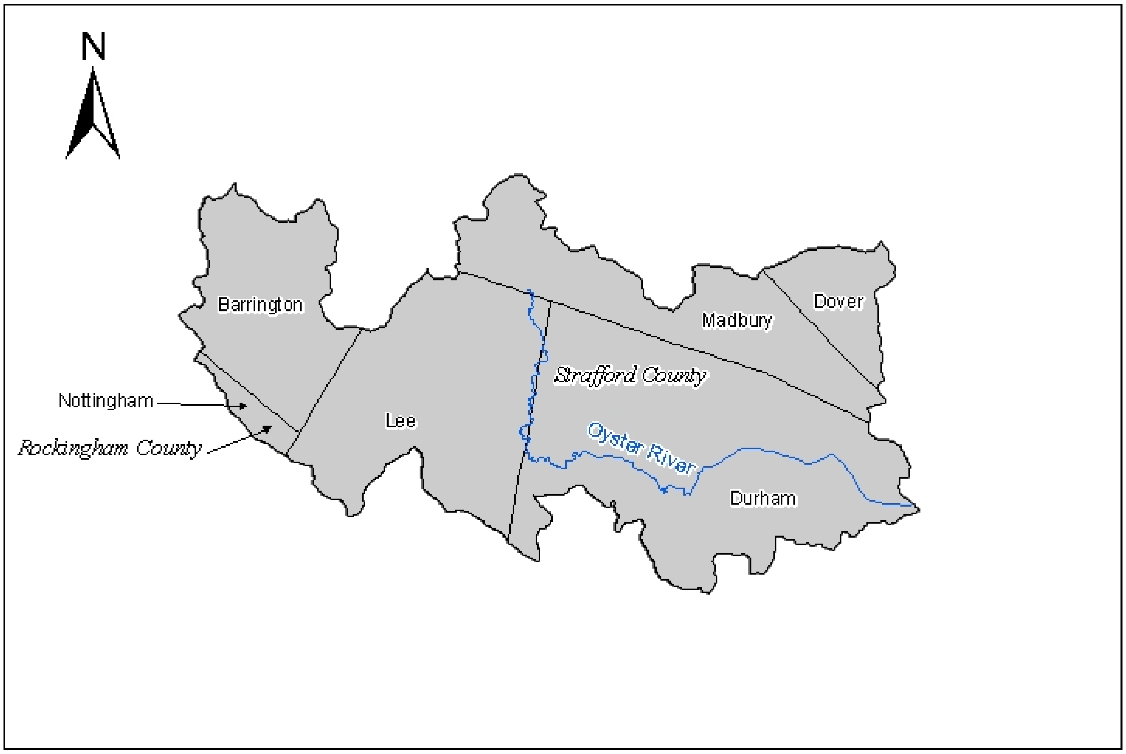

Figure A-1e: Oyster River Watershed

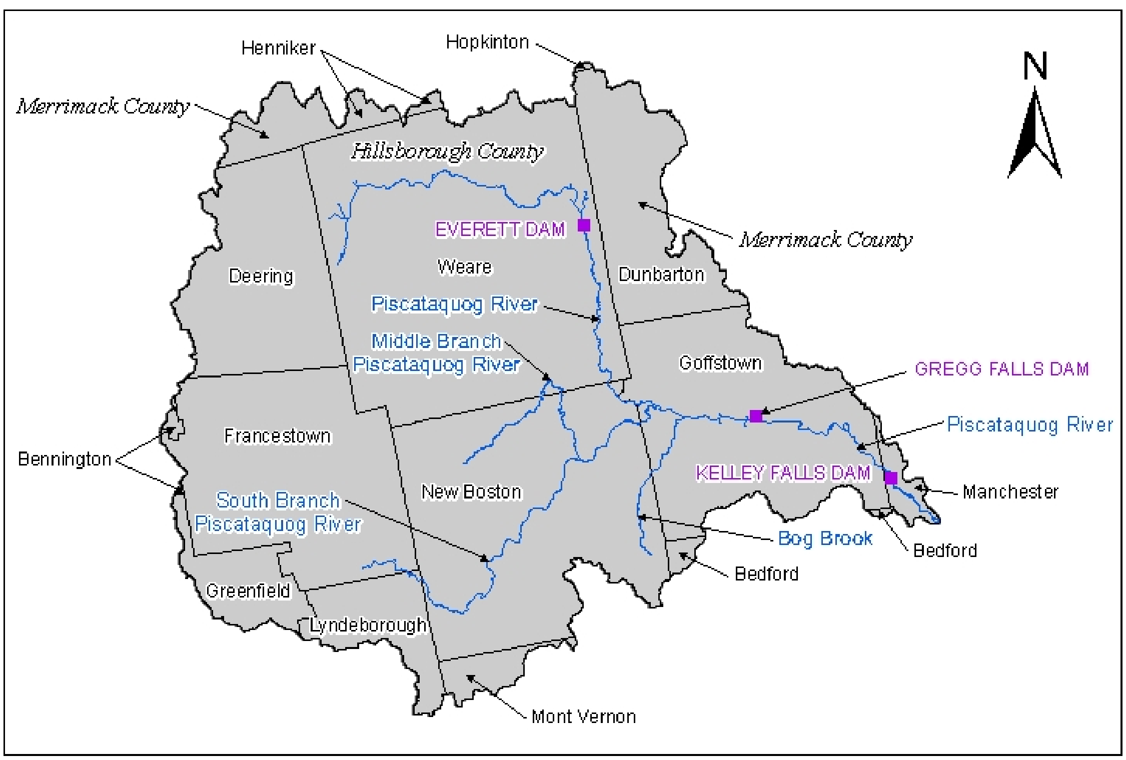

Figure A-1f: Piscataquog River Watershed

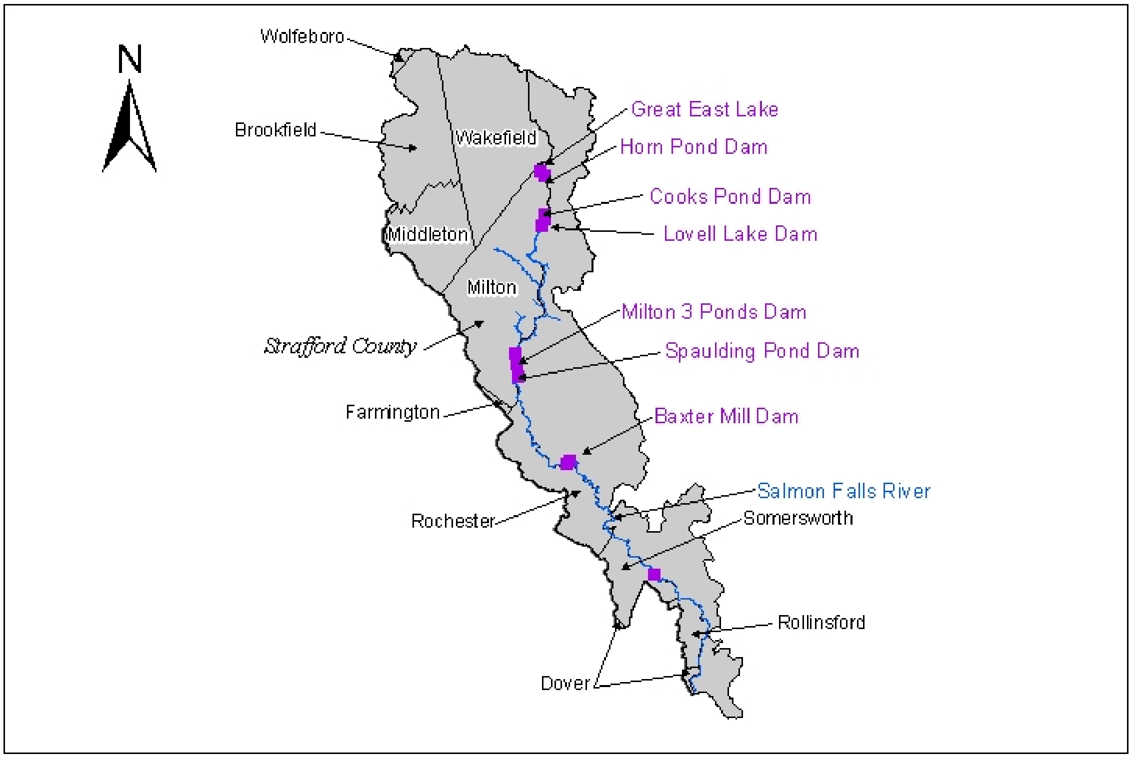

Figure A-1g: Salmon Falls River Watershed

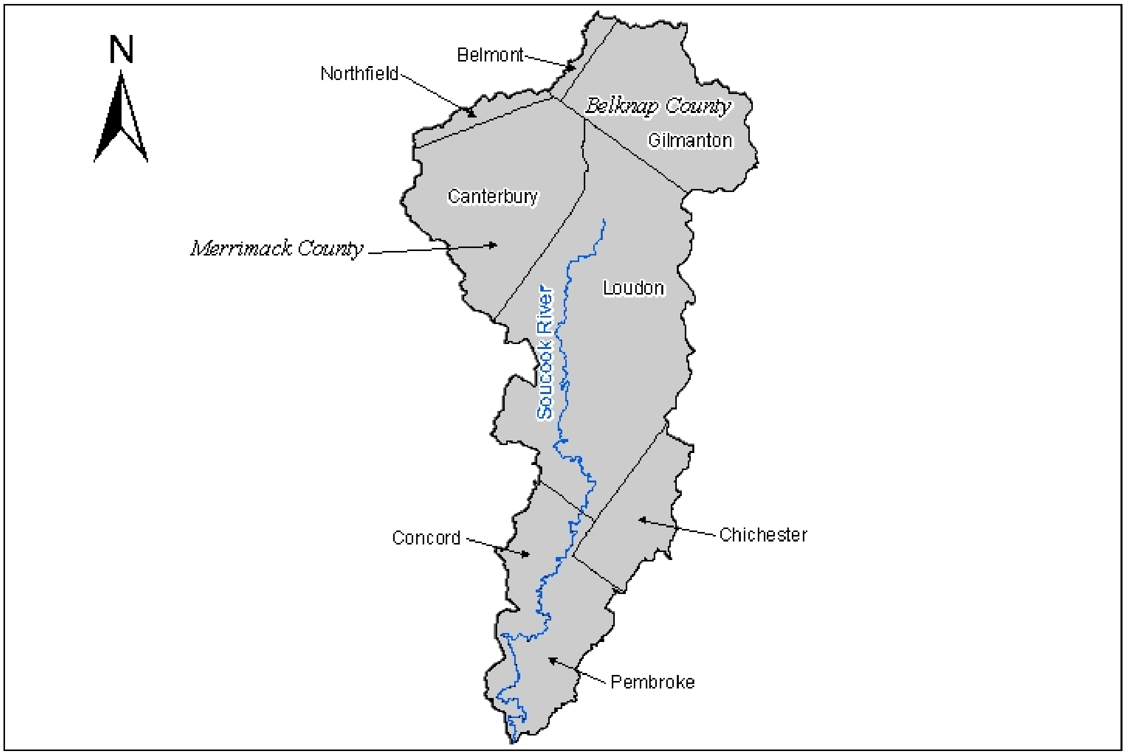

Figure A-1h: Soucook River Watershed

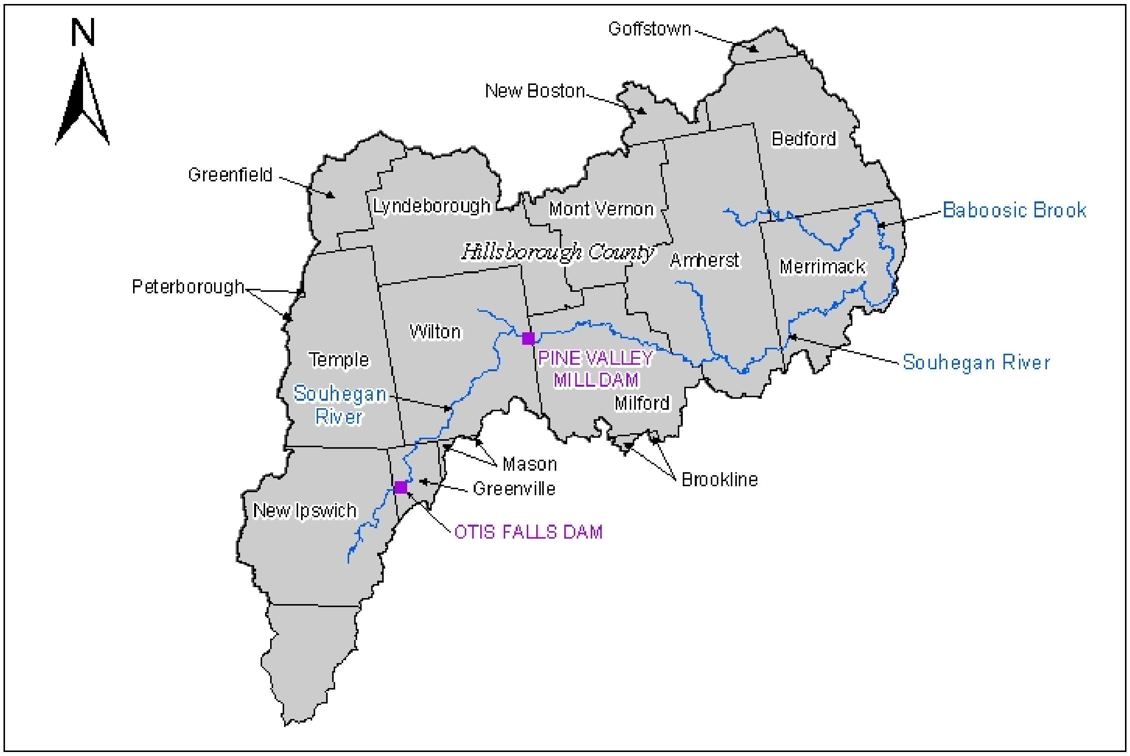

Figure A-1i: Souhegan River Watershed

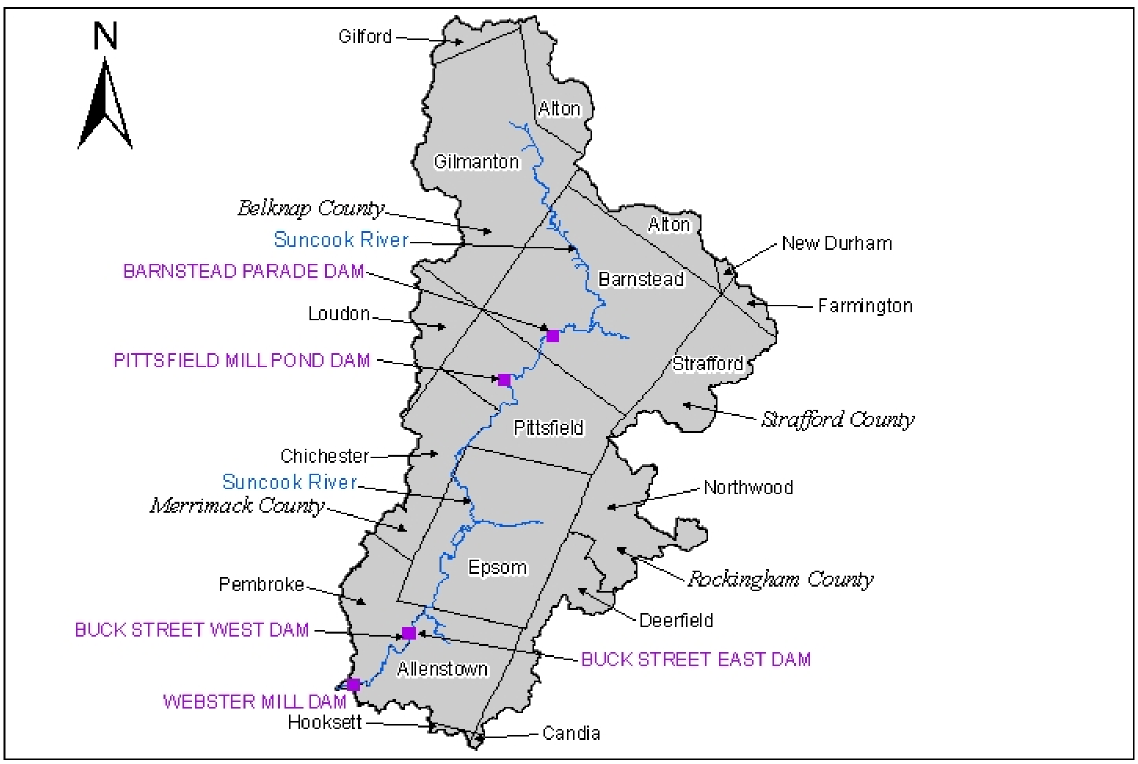

Figure A-1j: Suncook River Watershed

Previous Historical Flooding

New Hampshire has a long history of severe flooding prior to and including the May 2006 and April 2007 floods, as shown in Table A-1. Some of the most severe historic floods have occurred in March and April as a result of a combination of heavy spring rains, snowmelt, and ice jams. Coastal storms, in the form of nor'easters throughout the year, or tropical storms or hurricanes in late summer and fall have produced severe flooding occurs either in early spring or autumn. As a result major flooding events can and have occurred in all seasons, not just in the spring "runoff" season.

Table A-2: History of Flooding in New Hampshire (University of New Hampshire 2007)

Date	Area Affected (River Basins or Region)	Recurrence Interval (year)	Remarks
December 1740	Merrimack	Unknown	*First recorded flood in New Hampshire*
October 23, 1785	Cocheco, Baker, Pemigewasset, Contoocook and Merrimack	Unknown	*Greatest discharge at Merrimack and at Lowell, MA until 1902*
March 24–30, 1826	Pemigewasset, Merrimack, Contoocook, Blackwater and Ashuelot	Unknown	
April 21–24, 1852	Pemigewasset, Winnespaukee, Contoocook, Blackwater, and Ashuelot	Unknown	*Merrimack River at Concord - highest stream stage for 70 years. Merrimack River at Nashua - 2 feet lower than 1785*
April 19–22, 1862	Contoocook, Merrimack, Piscataquog, and Connecticut	Unknown	*Highest stream stages to date on the Connecticut River; due solely to snowmelt*
October 3–5, 1869	Androscoggin, Pemigewasset, Baker, Contoocook, Merrimack, Piscataquog, Souhegan, Ammonoosuc, Mascoma, and Connecticut	Unknown	*Tropical storm lasting 36 hours. Rainfall, 6–12 inches*
November 3–4, 1927	Pemigewasset, Baker, Merrimack, Ammonoosuc and Connecticut	25 to >5O	*Upper Pemigewasset River and Baker River - exceeded the 1936 flood. Down stream at Plymouth - less severe than the 1936 flood*
March 11–21, 1936	Statewide	25 to > 50	*Double flood; first due to rains and snowmelt; second, due to large rainfall*
September 21, 1938	Statewide	Unknown	*Hurricane. Stream stages similar to those of March 1936 and exceeded 1936 stages in Upper Contoocook River*

Date	Area Affected (River Basins or Region)	Recurrence Interval (year)	Remarks
June 1942	Merrimack River Basin	Unknown	*Fourth flood recorded in the lower Merrimack River basin at Manchester, NH*
June 15–16, 1943	Upper Connecticut, Diamond and Androscoggin	25 to >50	*Intense rainfall exceeding 4 inches; highest stream stages of record in parts of the affected area*
June 1944	Merrimack River	Unknown	*One of the five highest known floods at Manchester on the Merrimack*
November 1950	Contoocook River and Nubanusit Brook	Unknown	*Localized storm resulted in flooding of this area*
March 27, 1953	Lower Androscoggin, Saco, Ossipee, Upper Ammonoosuc, Israel, and Ammonoosuc	25 to>50	*Peak of record for the Saco and Ossipee Rivers*
August 1955	Connecticut River Basin	Unknown	*Heavy rains caused extensive damage throughout the basin area*
October 25, 1959	White Mountain Area; Saco, Upper Pemigewasset and Ammonoosuc Rivers	25 to >50	*Largest of record on Ammonoosuc at Bethlehem Junctions; third largest of record on the Pemigewasset and Saco Rivers*
December 1959	Piscataqua - Portsmouth	Unknown	*Northeaster brought tides exceeding maximum tidal flood levels in Portsmouth. Damage was heavy along the coast*
April 1960	Merrimack and Piscataquog	Unknown	*Flooding resulted from rapid melting of deep snow cover and the moderate to heavy rainfall. Third highest flood of record on the rivers*
April 1969	Merrimack River Basin	Unknown	*Record depth of snow cover in the Merrimack River Basin and elsewhere resulted in excessive snowmelt and runoff when combined with sporadic rainfall*
February 1972	Coastal Area	Unknown	*Coastal area was declared a National Disaster Area as a result of the devastating effects of a severe coastal storm, damage was extensive*
June 1972	Pemigewasset River	Unknown	*Five days of heavy rain caused some of the worst flooding since 1927 along streams in the upper part of the State, damage was extensive along the Pemigewasset River and smaller streams in northern areas*
June 30, 1973	Ammonoosuc River	25 to > 50	*Northwestern White Mountains*

Date	Area Affected (River Basins or Region)	Recurrence Interval (year)	Remarks
April 1976	Connecticut River	Unknown	*Rain and snowmelt brought the river to 1972 levels, flooding roads and croplands*
March 14,1977	South-central and Coastal New Hampshire	25 to 50	*Peak of record for Soucook River*
February 1978 (“The Blizzard of ‘78”)	Coastal New Hampshire	Unknown	*Nor’easter brought strong winds and precipitation to the entire State. Hardest hit area was the coastline, with wave action and floodwaters destroying homes. Roads all along the coast were breached by waves flooding over to meet the rising tidal waters in the marshes*
July, 1986–August 10,1986	Statewide	Unknown	*FEMA DR-71I-NH: Severe summer storms with heavy rains, tornadoes; flash flood and severe winds*
March 31–April 2, 1987	Androscoggin, Saco, Ossipee, Piscataquog, Pemigewasset, Merrimack and Contoocook River	25 to >50	*Caused by snowmelt and Sense rain Precursor to a significant, following event*
April 6–7, 1987	Lamprey River and Beaver Brook	25 to >50	*FEMA DR-789-NH: Large rainfall event following the March 31– April 2 storm*
August 7–11, 1990	Statewide	Unknown	*FEMA DR-876-NH: Series of storm events from August 7–11, 1990 with moderate to heavy rains during this period produced widespread flooding*
August 19, 1991	Statewide	Unknown	*FEMA DR-917-NH: Hurricane Bob struck New Hampshire causing extensive damage in Rockingham and Strafford counties, but the effects were felt statewide*
October–November 1995	Northern and Western Regions	Unknown	*FEMA DR-1144-NH: Counties declared: Grafton, Hillsborough, Merrimack, Rockingham, Strafford, and Sullivan*
October 1996	Northern and Western Regions	Unknown	*FEMA DR-1077-NH: Counties declared: Carroll, Cheshire, Coos, Grafton, Merrimack, and Sullivan*

Date	Area Affected (River Basins or Region)	Recurrence Interval (year)	Remarks
June–July, 1998	Central and Southern Regions	Unknown	*FEMA DR-1231-NH: Series of rainfall events. Counties declared: Belknap, Grafton, Carroll, Merrimack, Rockingham, and Sullivan (1 fatality). (Several weeks earlier, significant flooding, due to rain and rapid snowpack melting, occurred in Coos County, undeclared in this event. Heavy damage to secondary roads occurred)*
September 18–19, 1999	Central and Southwest Regions	Unknown	*FEMA DR-1305-NH: Heavy rains associated with Tropical Storm/Hurricane Floyd. Counties declared: Belknap, Cheshire, and Grafton*
July 21–August 18, 2003	Southwestern Region	Unknown	*FEMA-1489-DR: Severe storms and flooding occurred in Cheshire and Sullivan counties. Public Assistance provided for repair of disaster damaged facilities*
October 7–16, 2005	Southwestern Region	Exceeded 100 in some areas	*FEMA-1610-DR: Heavy rains associated with Tropical Storm Tammy and Subtropical Depression 22 resulted in 6–15 inches of rain*
May 13–15, 2006	Central and Southern NH	Exceeded 100	*FEMA-1643-DR: Heavy rainfall 8–16 inches*
April 27, 2007	Statewide	100	*FEMA-1695-DR: Severe storms and flooding, starting on April 15th*

A-2.0 MAY 2006 FLOOD

Major flooding occurred in several river basins in central and southern New Hampshire from May 13 through May 17, 2006. Widespread, significant property damage, along with road closures and evacuations of residential areas resulted in the issuance of a Presidential Major Disaster Declaration on May 25, 2006, for Belknap, Carroll, Grafton, Hillsborough, Merrimack, Rockingham, and Strafford Counties. The most severe flooding, with peak discharge recurrence intervals in excess of 50 years, occurred in coastal areas of the Piscataqua-Salmon Falls River basin, including the Cocheco, Lamprey, and Salmon Falls River basins, and in south-central New Hampshire in the Contoocook, Piscataquog, Soucook, and Suncook River basins (see Figure A-2). According to published U.S. Geologic Service (USGS) records, record peak flood discharges were recorded at 14 stream gages with more than 10 years of record in New Hampshire; although at three of these gage locations the May 2006 peak of record would be superseded in April 2007 (see Table A-1). Peak discharges with recurrence interval of flooding equal to or in excess of 50 years were observed at 14 stream gages; at 8 of these gages the recurrence interval of flooding was equal to or greater than 100 years (Olsen 2007).

A-2.1 Antecedent Conditions

A-2.2 Antecedent Meteorological Conditions

Moisture conditions in the months leading up to the May 2006 flood can be characterized by examining average precipitation for the period December 2005 through May 2006 (see Figure A-3). Statewide precipitation exceeded the long-term (1971–2000) average for December and January, but was below the long-term average for the months of February, March, and April (see Table A-1).

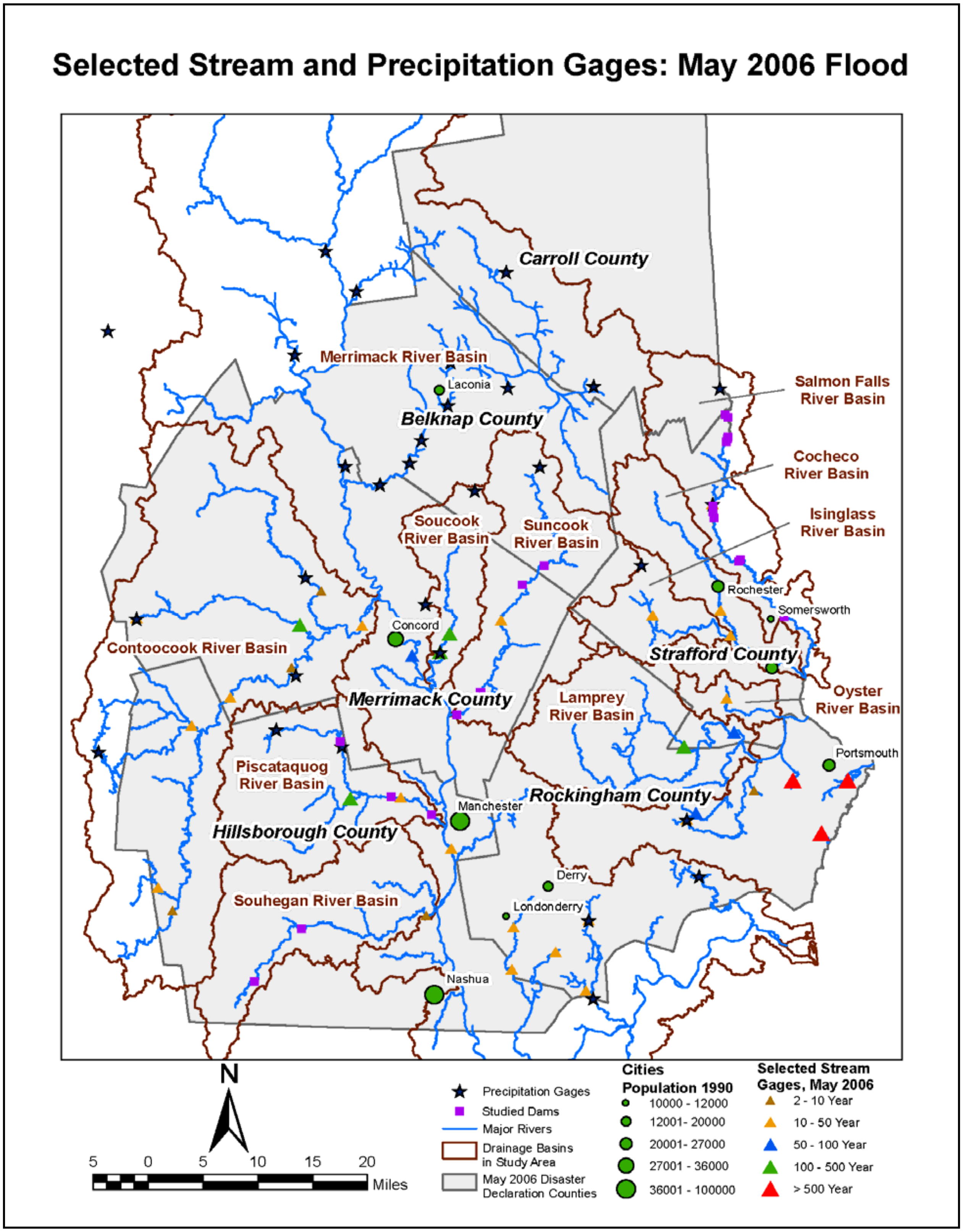

Figure A-2: May 2006 Study Area Map, Showing Selected Streams, Gages, and Dams

Table A-3: Statewide Average New Hampshire Precipitation for December 2005 Through May 2006

Month	Statewide Average Precipitation (inches)	Average Monthly Precipitation, 1971–2000 (inches)	Percent of Long-Term Average	Rank (1 = wettest, 112 = driest)
December 2005	4.29	3.44	124%	25
January 2006	4.14	3.42	120%	25
February 2006	2.43	2.62	92%	68
March 2006	1.39	3.37	41%	108
April 2006	3.12	3.50	89%	64
May 2006	9.30	3.77	247%	2

In the first 12 days of May 2006, Concord, Manchester, and Portsmouth, New Hampshire received a total of 1.7, 2.2, and 2.3 inches of rain, respectively (see Figure A-4). As a result of this rainfall in early May, soil moisture conditions for the study area were at higher than average levels, resulting in greater than average runoff response during the May 2006 flood.

A-2.2.1 Antecedent Stream Flow Conditions

In order to characterize the stream flow conditions prior to the May 2006 flood event, daily mean discharges for April and May 2006 were compared to long-term median (or 50th percentile) daily discharges at USGS stream gages on the Salmon Falls, Oyster, Lamprey, Contoocook, Soucook, and Souhegan Rivers (see Figure A-5). In general, this comparison indicates that daily discharges on the Salmon Falls and Contoocook Rivers were less than the long-term median daily discharges for all of April and early May 2006; although small rises were noted, the daily discharges on these rivers did not exceed the median discharge values until the onset of major flooding on May 13, 2006. Daily discharges on the Soucook and Souhegan Rivers were generally less than median discharge values throughout the period prior to the onset of major flooding; however for these two streams the three relatively small rises on April 5, April 25, and May 4, resulted in daily discharges that were nearly equal to or slightly greater than the median discharges values. Daily discharges on the Oyster and Lamprey Rivers were generally nearly equal to slightly greater than the median discharge values for most of the period from early April through May 12; in addition the daily discharges for these two rivers remained greater than the median discharge values for the week between the small rise on May 4 and the onset of major flooding on May 13.

A further review of median discharge values for several long-term stream gages (see Figure A-6) show that, in general, median flow values follow a fairly regular flow pattern typically increasing through winter until reaching yearly maximum values in April and then begin a recession that lasts throughout spring-and summer. As such, the May 2006 flooding occurred during the typical spring recession.

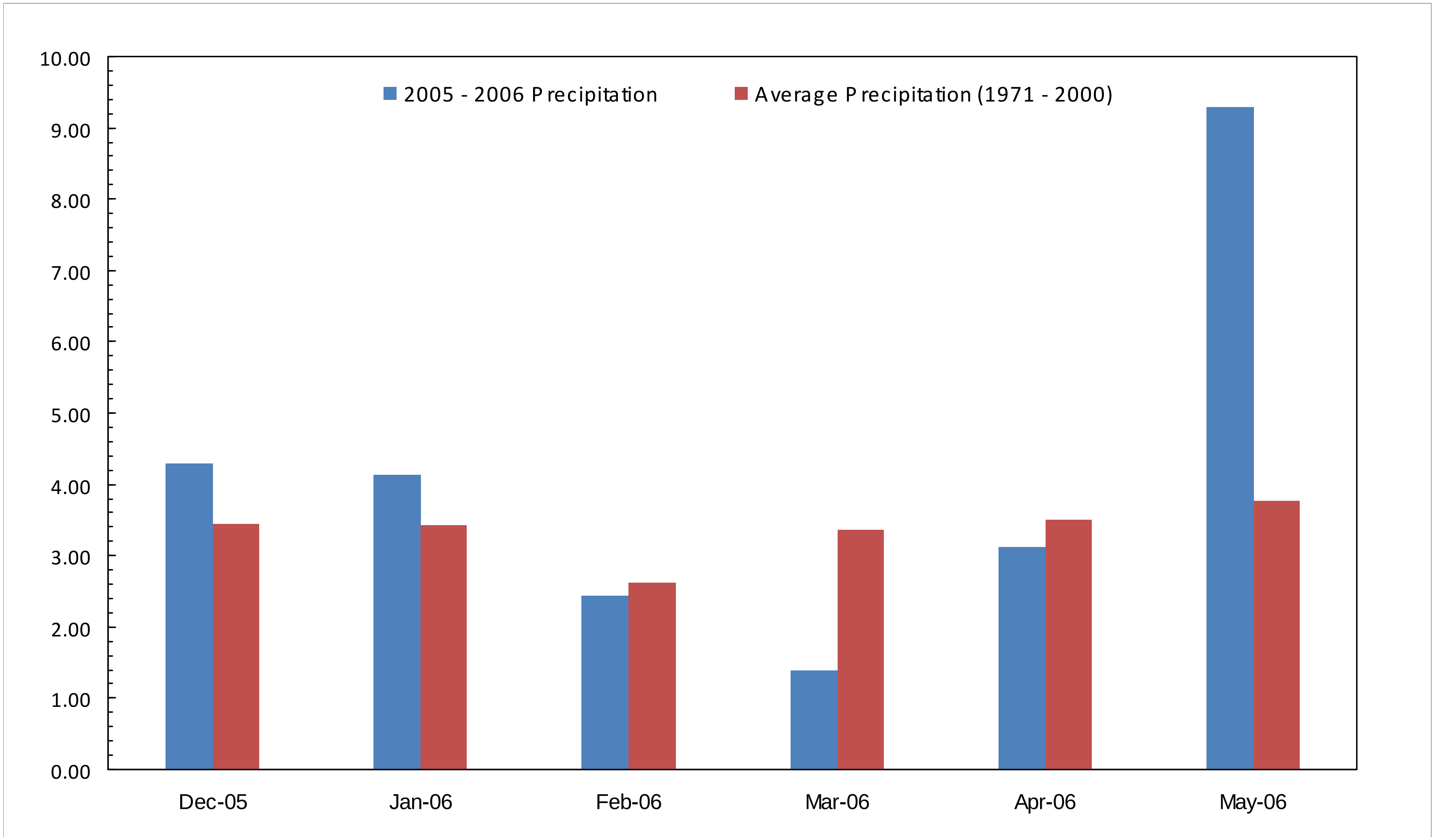

Figure A-3: New Hampshire Monthly Precipitation for Winter and Spring 2005-2006

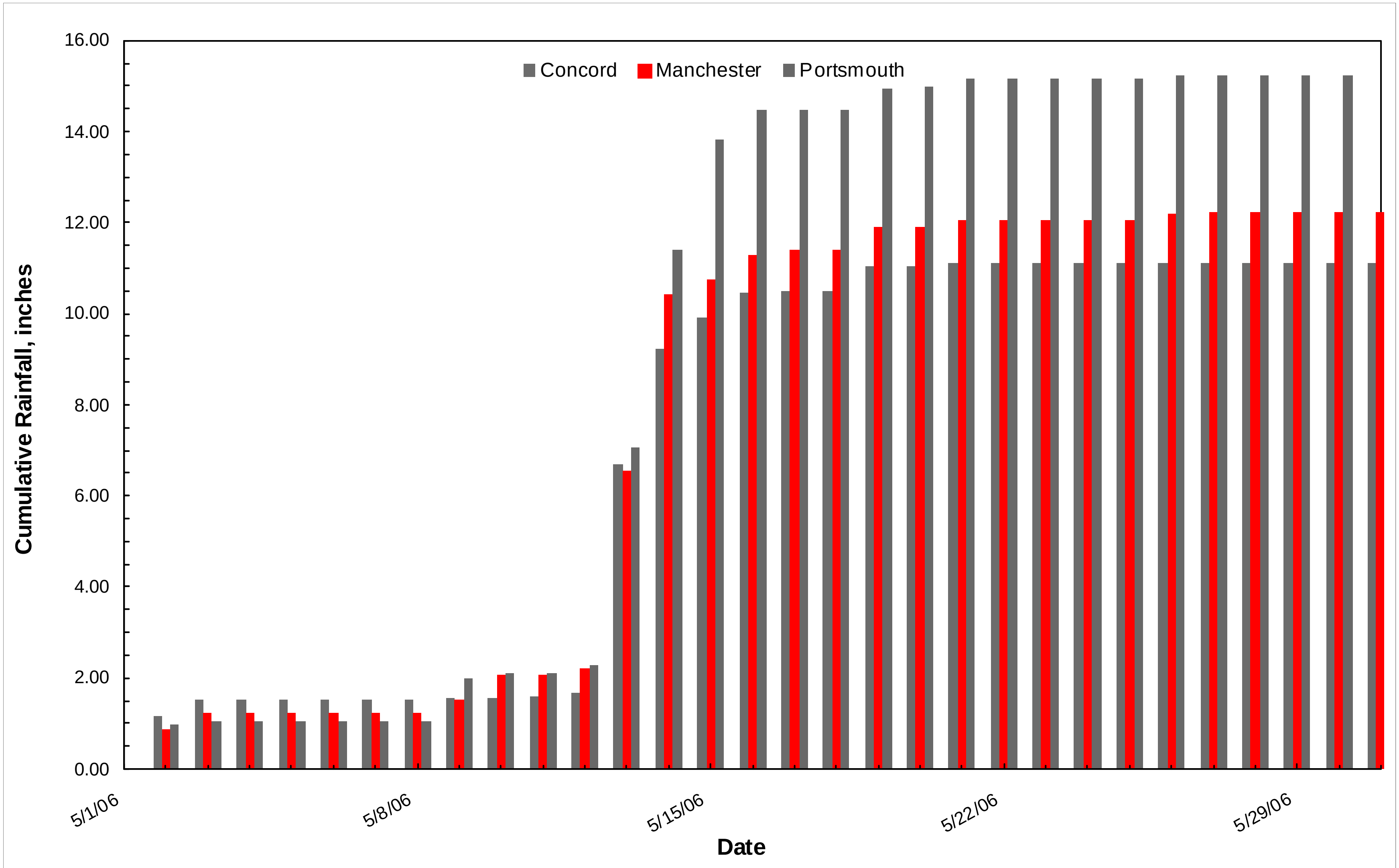

Figure A-4: Cumulative Daily Rainfall Totals, May 2006

Figure A-5: Daily and Long-Term Median Discharges

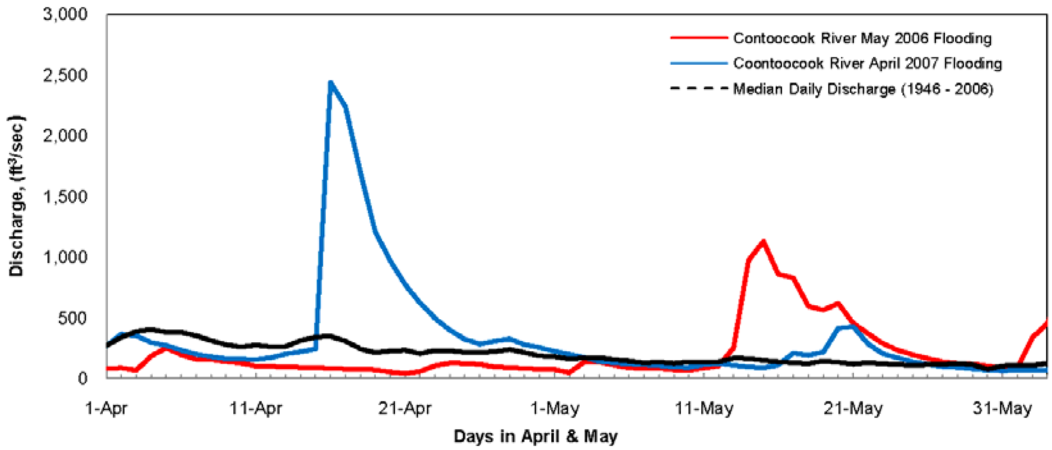

Figure 5a. Contoocook River Daily and long-term Median Discharges

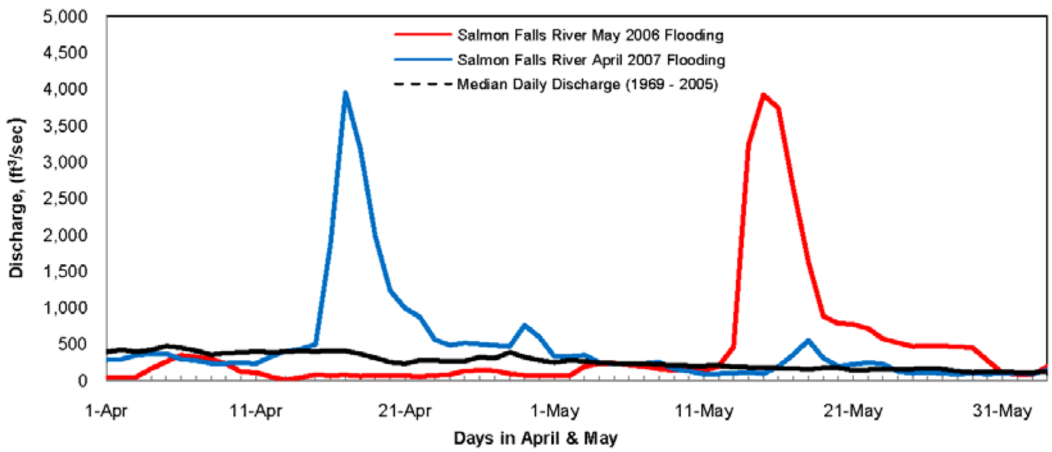

Figure 5b. Salmon Falls River Daily and long-term Median Discharges

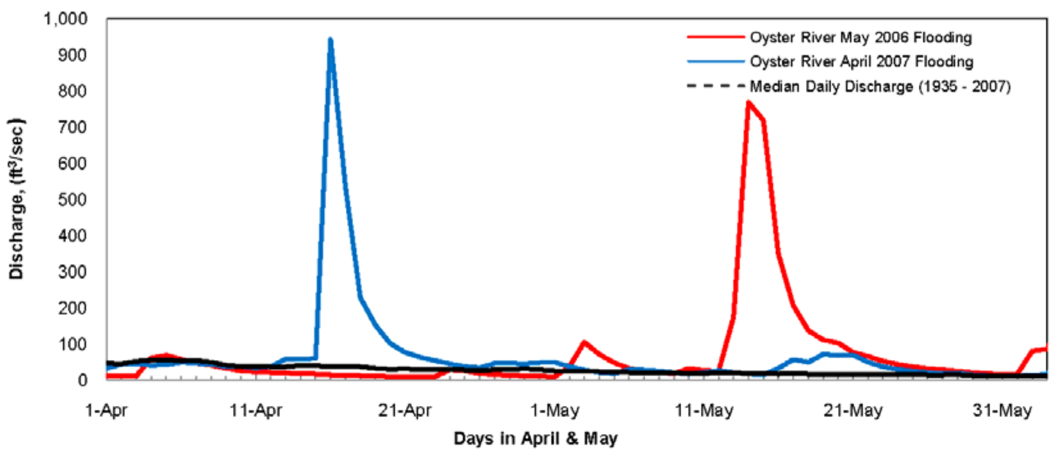

Figure 5c. Oyster River Daily and long-term Median Discharges

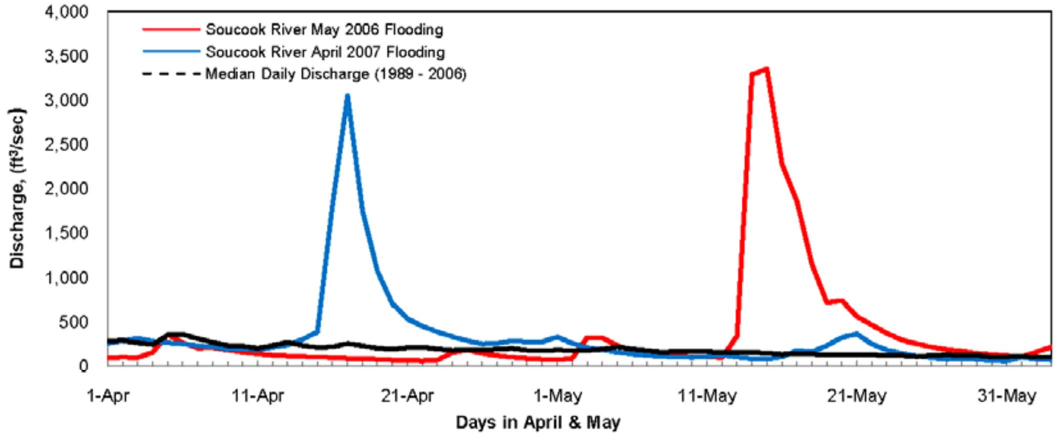

Figure 5d. Soucook River Daily and long-term Median Discharges

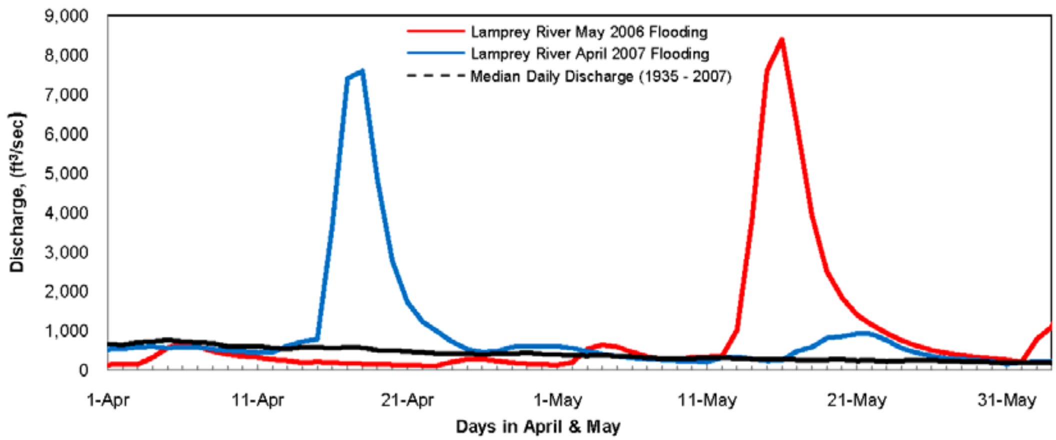

Figure 5e. Lamprey River Daily and long-term Median Discharges

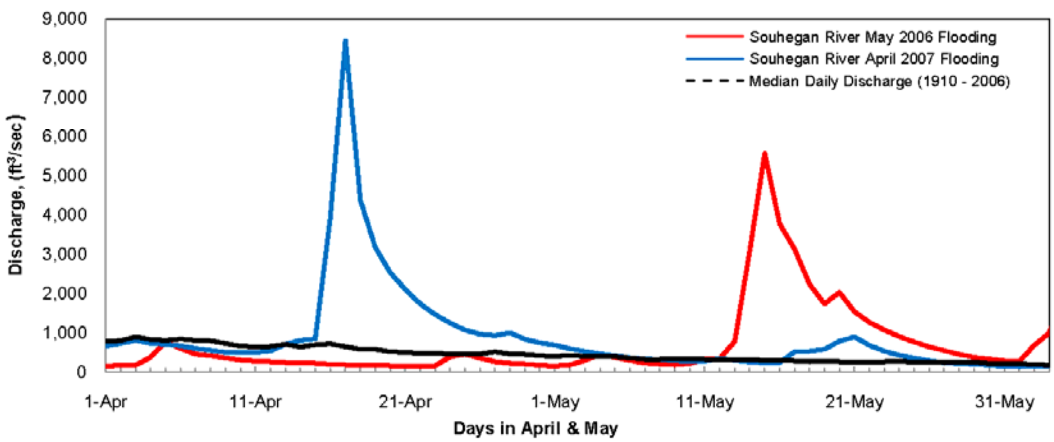

Figure 5f. Souhegan River Daily and long-term Median Discharges

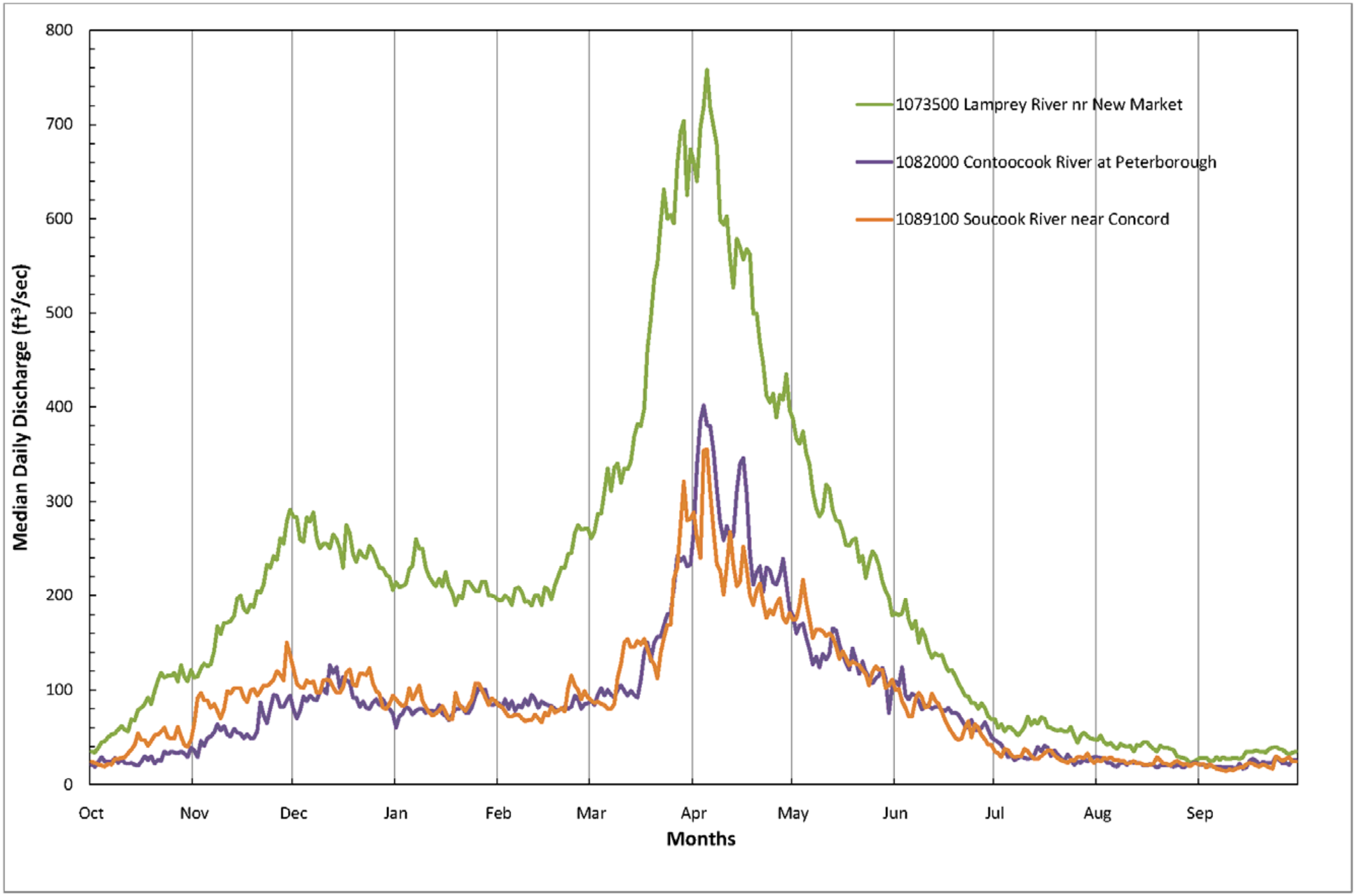

Figure A-6: Long-Term Median Daily Flow Values at Selected Gage Locations

A-2.3 Precipitation

The rainfall that produced the May 2006 flooding began on May 12 and continued through May 16, 2006, resulting in more than 12 inches of rain in the vicinity of Portsmouth, along the New Hampshire seacoast, and approximately 9 inches of rain in the vicinity of Concord and Manchester, in the south-central part of the State. The most intense rainfall occurred from May 13 through and May 15, with more than 90 percent of the 5-day storm total falling on these 3 days. The rainfall distribution and amount for May 15th, at the height of the storm, is shown in Figure A-7. In comparison to computed estimates of rainfall frequency presented in the National Oceanic and Atmospheric Administration's Technical Paper 40, *Rainfall Frequency Atlas of the United States* (NOAA TP-40), the greatest 1-day rainfall (May 13) is roughly equal to the 24-hour, 25-year recurrence interval values, while the 2-day (May 13–14) total rainfall amounts during the storm event exceed the 2-day, 100-year recurrence interval values (see Table A-3). As noted in previous section, significant precipitation was also received in the first 12 days of May 2006 as well; making May 2006 the second wettest May since 1895. There was substantial precipitation variability in the study area; precipitation in the Souhegan River Basin was substantially less than in the cities shown in Table A-3.

Table A-4: 24-Hour and 2-Day Rainfall Amounts for May 2006 Flood (National Weather Service Precipitation Analysis 2008)

Location	May 13, 2006 Rainfall Total (inches)	24-Hour Rainfall			May 13–14, 2006 Rainfall Total (inches)	2-Day Rainfall		
		25-year	50-year	100-year		25-year	50-year	100-year
Portsmouth	4.8	5.1	5.5	6.3	9.1	6.0	6.7	7.5
Manchester	4.4				8.2			
Concord	5.0				7.6			

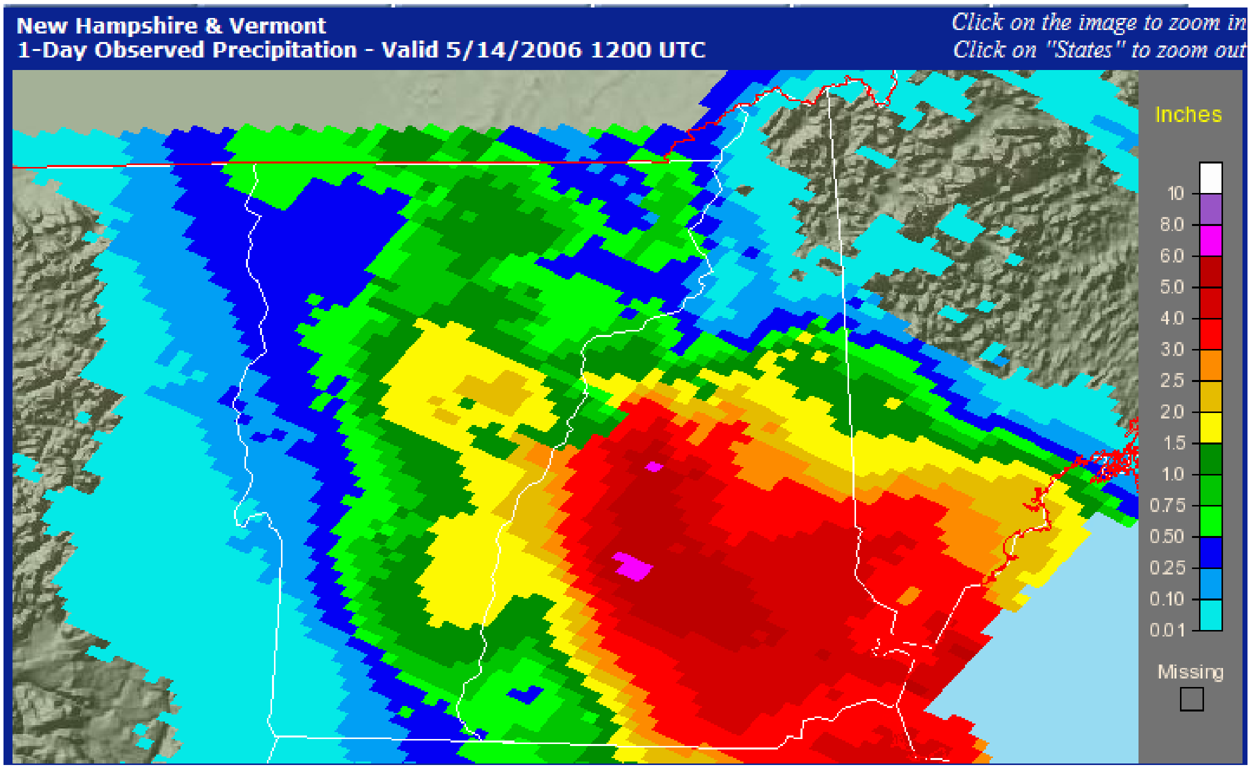

Figure A-7: Radar Rainfall Estimates for May 15, 2006 (NWS 2008h)

A-2.4 Flood Discharges

Peak discharges with a recurrence interval of flooding equal to or in excess of 50 years were observed at 14 stream gages; at 8 of these gages the recurrence interval of flooding was equal to or greater than 100 years (USGS, 2007). Record peak discharges were set at 14 long-term stream gages in the Cocheco, Contoocook, Lamprey, Piscataquog, Salmon Falls, and Soucook river basins; although the May 2006 peak of record would be superseded in April 2007 on the Salmon Falls, Cocheco, and South Branch Piscataquog Rivers (see Table A-1).

Flooding with recurrence interval of 500 years or greater was observed in small coastal drainage areas along the New Hampshire seacoast. Recurrence intervals between 100 and 500 years were observed on the main stem of the Soucook River. In addition, 100–500-year flooding was observed on tributaries of the Lamprey, the Piscataquog, and the Contoocook Rivers.

Runoff, in inches over the upstream drainage area, was computed for seven USGS stream gages (see Table A-1). Computed runoff at these seven gages ranged between a maximum of 7.8 inches to a minimum of 3.8 inches, with an average values of 6.1 inches.

Hydrographs (or plots of river gage height versus time), along with rainfall vs. time plots of the May 2006 and April 2007 flooding on the Piscataquog and Souhegan are presented for comparison (see Figure A-8). In general, comparison of the observed rainfall patterns at the two locations indicate that although the May 2006 rain event was longer in duration and resulted in more total rainfall, the rainfall for the April 2007 was more intense. This comparison is evident in the more rapid initial rise observed in the April 2007 hydrographs for both the Piscataquog and Souhegan Rivers. In addition, the May 2006 hydrographs are somewhat wider than those observed for the April 2007 event, indicating an overall larger amount of direct runoff.

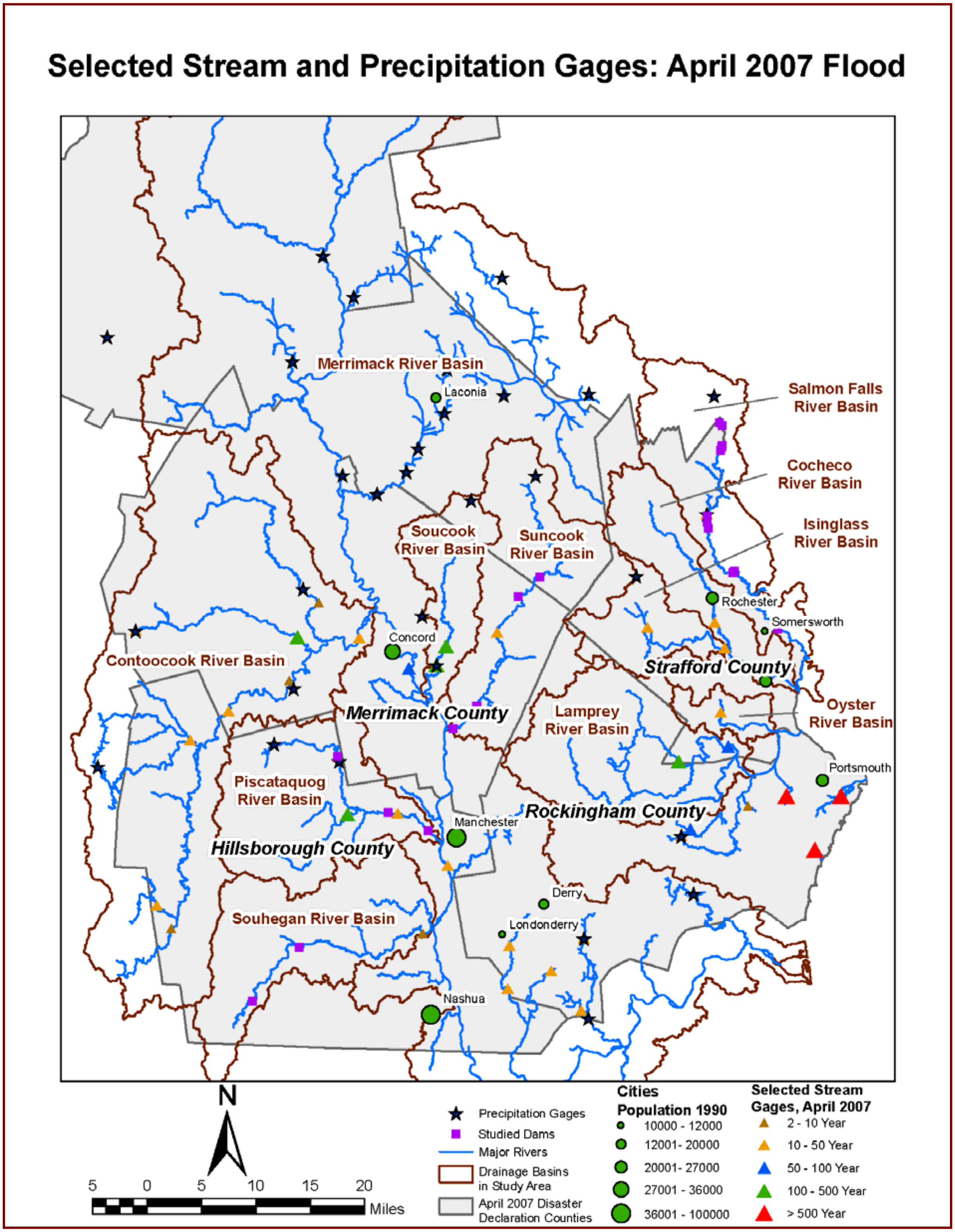

Figure A-8: April 2007 Study Area Map, Showing Selected Streams, Gages, and Dams

A-3.0 APRIL 2007 EVENT

Major flooding again occurred in central and southern New Hampshire from April 15 through 19, 2007. Widespread damage across the area resulting in the second Presidential Major Disaster Declaration in less than a year on April 27, 2007, for five counties: Grafton, Hillsborough, Merrimack, Rockingham, and Strafford; Belknap County was added to the Disaster Declaration on May 10, 2007. The most severe flooding, with peak discharge recurrence intervals in excess of 50 years, occurred in the coastal areas of the Piscataqua-Salmon Falls River basin, including the Lamprey and Oyster River basins, and in south-central New Hampshire in the Contoocook, the Piscataquog, the Souhegan, and the Suncook River basins (see Figure A-9). According to published USGS records, record peak flood discharges were recorded at six stream gages in New Hampshire (see Table A-1). Peak discharges with recurrence intervals of flooding equal to or in excess of 50 years were observed at 10 stream gages; at 7 of these gages the recurrence interval of flooding was equal to or greater than 100 years (USGS, 2008).

A-3.1 Antecedent Conditions

A-3.1.1 Antecedent Meteorological Conditions

Moisture conditions in the months leading up to the April 2007 flood can be characterized by examining average precipitation for the period November 2006 through April 2007 (see Figure A-9). Statewide precipitation was greater than or equal to the long-term (1971–2000) average for each of the 5 months leading up to the April 2007 flood except for February 2007 (see Table A-4).

Table A-5: Statewide Average New Hampshire Precipitation for November 2006 Through April 2007

Month	Statewide Average Precipitation (inches)	Average Monthly Precipitation, 1971–2000 (inches)	Percent of Long-Term Average	Rank (1 = wettest, 112 = driest)
November 2006	4.69	3.44	119%	34
December 2006	3.42	3.42	99%	55
January 2007	3.12	2.62	91%	53
February 2007	2.04	3.37	77%	90
March 2007	3.61	3.50	107%	49
April 2007	7.35	3.50	209%	1

In the first 14 days of April 2007, Concord, Manchester, and Portsmouth, NH, received a total of 2.1, 2.2, and 2.2 inches of precipitation, respectively (see Figure A-10). In addition, a total of 10.5 inches of snow was recorded at Concord during the first 14 days of the month and 1.0 inch of snow remained on the ground as of April 14. Snowfall for the month was greater and remaining snow depths were greater in higher elevation areas of the State. As a result of the snow and rain precipitation in early April, soil moisture conditions for the study area were nearly 100 percent saturated. The melting snow released the water to the soil, resulting in much greater than average runoff response during the April 2007 flood.

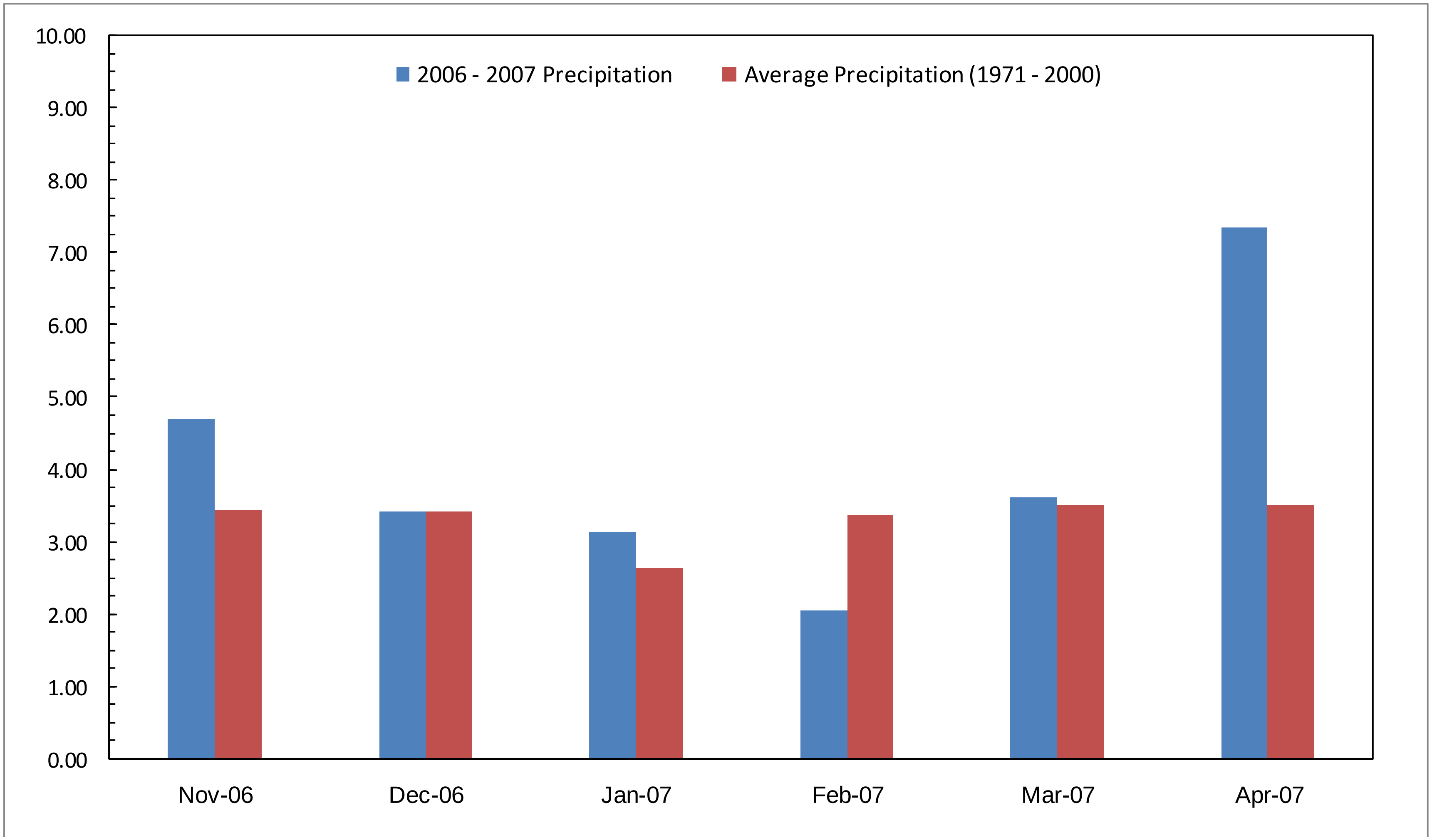

Figure A-9: New Hampshire Monthly Precipitation for Winter and Spring 2006–2007

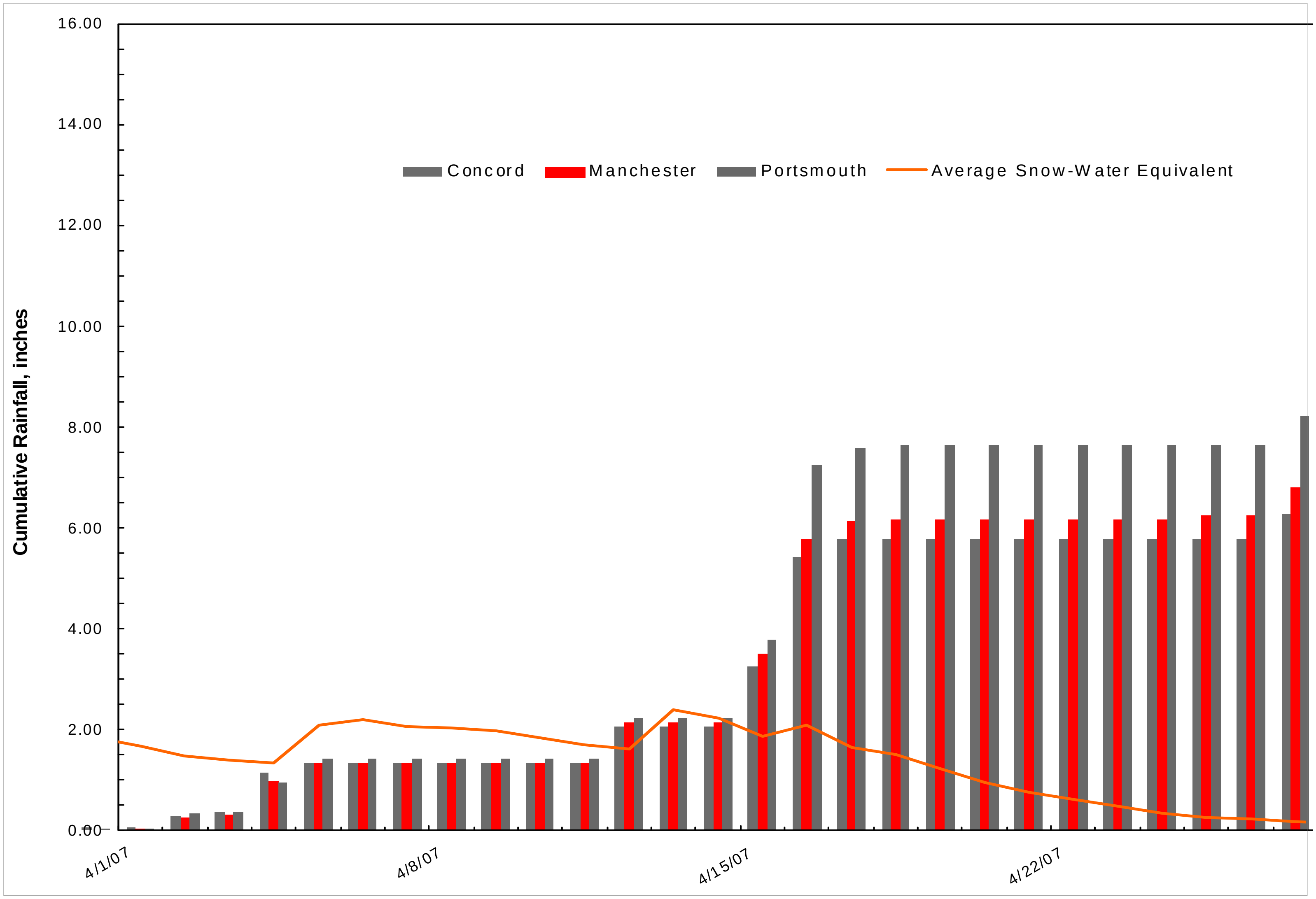

Figure A-10: Cumulative Daily Rainfall Totals, April 2007

A-3.1.2 Antecedent Stream Flow Conditions

In order to characterize the stream flow conditions prior to the April 2007 flood event, daily mean discharges for March and April 2007 were compared to long-term median (or 50th percentile) daily discharges at USGS stream gages on the Salmon Falls, Oyster, Lamprey, Contoocook, Soucook, and Souhegan Rivers (see Figure A-5). In general, this comparison indicates that daily discharges on the Salmon Falls River were less than the long-term median daily discharges for all of March and early April 2007; although small rises were noted, the daily discharges on the Salmon Falls River did not exceed the median discharge values until the onset of major flooding on April 15, 2007. Daily discharges on the Oyster, Lamprey, Contoocook, Soucook, and Souhegan Rivers were for the most part equal to or in excess of the median discharge values throughout the period prior to the onset of major flooding, with the exception of a few short periods of recession following some small rises.

A further review of median discharge values for several long-term stream gages (see Figure A-6) show that, in general, median flow values follow a fairly regular flow pattern such that median flow values typically increase through winter until reaching yearly maximum values in April and then begin a recession that lasts throughout spring and summer. As such, the April 2007 flooding occurred during the typical peak period of maximum flows.

A-3.2 Precipitation

The precipitation that produced the April 2007 flooding began on April 15 as accumulating snow across most of New Hampshire. The snowfall had changed over to heavy rainfall by the afternoon and evening of April 15 and continued as rain throughout the 16th before ending in most areas on the April 17. Rainfall distribution and total amounts for April 16th, the heaviest day of rainfall, are shown in Figure A-11. Total rainfall amounts of more than 5 inches in the vicinity of Portsmouth, along the New Hampshire seacoast, and approximately 4 inches of rain in the vicinity of Concord and Manchester, in the south-central part of the State. The most intense rainfall occurred on April 15-16, with more than 90 percent of the 3-day storm total falling on those 2 days. In comparison to computed estimates of rainfall frequency (NOAA TP-40), the April 16 total rainfall amounts for the coastal areas are approximately equal to the 24-hour, 5-year recurrence interval values, while in the south central areas of the State, the rainfall amounts were approximately equal to the 24-hour, 2-year amounts; the 2-day (April 15–16) total rainfall amounts along the seacoast during the storm event exceed the 2-day, 10-year recurrence interval values (see Table A-5). As noted in previous section, significant precipitation in the form of 12 inches of snow fell during the first 14 days of April. This snowfall provided as much as 2 inches additional snow-water equivalent during the period of heaviest rainfall. The heavy rain and snowfall received in April 2007 resulted in April 2007 being the second wettest April in since 1895 and the ninth snowiest April since 1868.

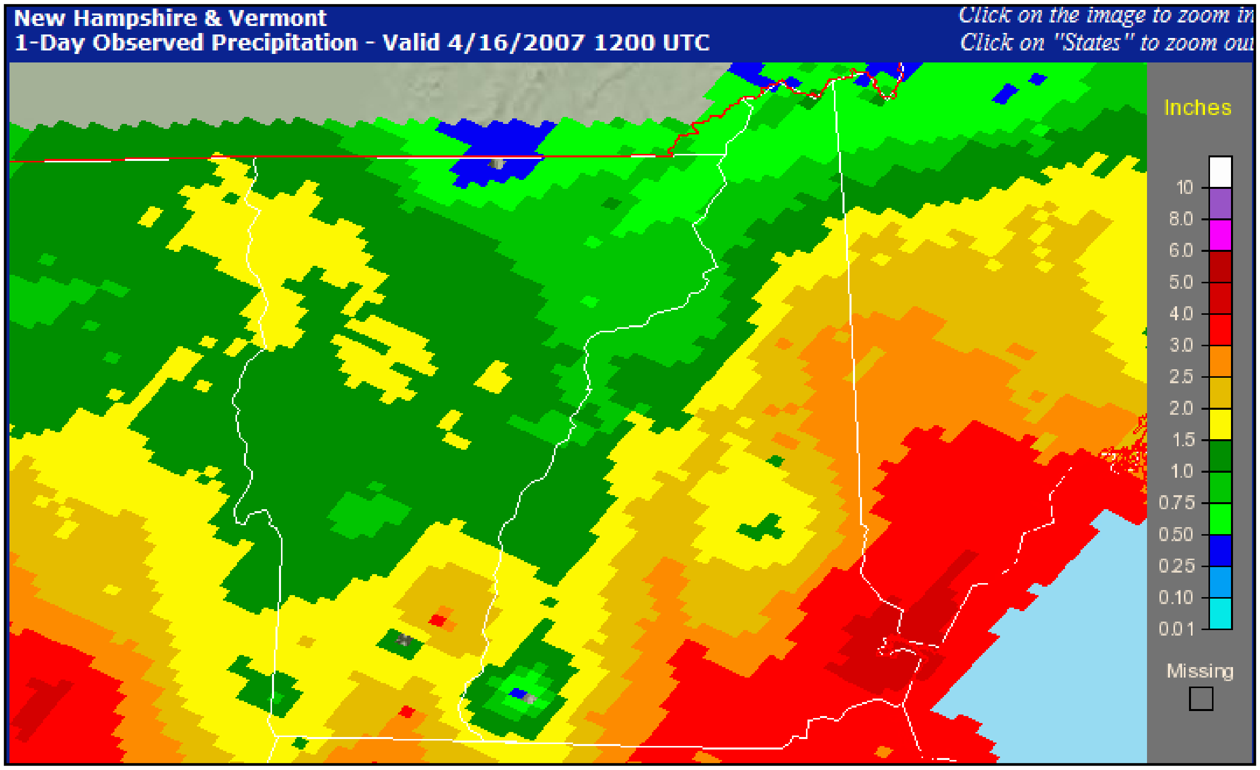

Figure A-11: Radar Rainfall Estimates for April 16, 2007 (NWS 2008i)

The rainfall on April 16 was greatest in southeastern New Hampshire, along the Atlantic Coast (see Figure A-11); in the coastal drainage basins of the Lamprey, Oyster, and Salmon Falls River. However, there were areas of heavier rain in the south-central part of the State in the Souhegan River Basin, and upper reaches of the Contoocook and Piscataquog River Basin. These areas of heaviest rainfall coincide with the areas of highest recurrence interval flooding (see Figure A-11).

Table A-6: 24-Hour and 2-Day Rainfall Amounts for April 2007 Flood (National Weather Service Precipitation Analysis 2008)

Location	April 16, 2007 Rainfall Total (inches)	24-hour Rainfall			April 15–16, 2007 Rainfall Total (inches)	2-Day Rainfall		
		2-year	5-year	10-year		2-year	5-year	10-year
Portsmouth	3.5				5.0			
Manchester	2.3	2.9	3.6	4.3	3.6	3.5	4.5	5.0
Concord	2.1				3.3			

A-3.3 Flood Discharges

Peak discharges with recurrence intervals of flooding equal to or in excess of 50 years were observed at 10 stream gages; at 7 of these gages the recurrence interval of flooding was equal to or greater than 100 years (USGS, 2007). Record peak discharges were set at six stream gages with more than 10 years of record on the Cocheco, Contoocook, Oyster, Salmon Falls, South Branch Piscataquog, and Suncook River; on the Cocheco, Salmon Falls, and South Branch Piscataquog Rivers, the record peak discharge superseded a record peak set during the May 2006 flood (see Table A-1).

Flooding with recurrence interval of 500 years or greater was observed at the Taylor River at Old Stage Road near Hampton (01073838) along the seacoast. In addition, the recurrence interval of flooding at South Branch Piscataquog River near Goffstown (1091000) exceeded 500 years at this long term gaging station. Recurrence intervals between 100 and 500 years were observed in several small coastal drainage areas along the New Hampshire seacoast as well as on the Suncook River and the Oyster River. Flooding with recurrence intervals between 50 and 100 years was observed on the Souhegan and Lamprey rivers and on the Warner River, a tributary to the Contoocook River.

Runoff, in inches over the upstream drainage area, was computed for seven USGS stream gages (see Table A-6). Computed runoff at these seven gages ranged between a maximum of 6.2 inches to a minimum of 4.4 inches, with an average values of 5.5 inches.

Hydrographs (or plots of river gage height versus time), along with rainfall vs. time plots of the May 2006 and April 2007 flooding on the Piscataquog and Souhegan were examined). In general, comparison of the observed rainfall patterns at the two locations indicate that although the May 2006 rain event was longer in duration and resulted in more total rainfall, the rainfall for the April 2007 was more intense. This comparison is evident in the more rapid initial rise observed in the April 2007 hydrographs for both the Piscataquog and Souhegan Rivers. In addition, the May 2006 hydrographs are somewhat wider than those observed for the April 2007 event, indicated an overall larger amount of direct runoff.

Table A-7: Peak Discharges, Estimated Return Periods, and Other Characteristics for Selected Stream Gages Affected by May 2006 and April 2007 Flooding

n.d., not determined n/a, not available

Gage Station Number	Gage Station Name	Period of Record	Return Period Discharge (cfs)				May 2006 Flood			April 2007 Flood			Maximum Peak of Record
			10-year	50-year	100-year	500-year	Peak Flow (cfs)	Return Period (years)	Runoff (inches)	Peak Flow (cfs)	Return Period (years)	Runoff (inches)	
01072100	Salmon Falls River at Milton, NH	1968–2007	3,190	5,590	6,920	10,900	5,450	10–50	5.0	5,500	10–50	5.5	April 2007
01072800	Cocheco River near Rochester, NH	1995–2007	5,350	9,920	12,500	20,300	5,550	10–50	n.d.	7,240	10–50	n.d.	April 2007
01072870	Isinglass R at Rochester Neck Rd near Dover, NH (see note 1)	2003–2007	2,920	4,680	5,620	8,230	4,370	10–50	n.d.	4,540	10–50	n.d.	n/a
01072880	Cocheco River at Spaulding Turnpike at Dover, NH (see note 1)	1992–1996	6,040	9,300	11,100	15,800	10,800	50–100	n.d.	n.d.	n.d.	n.d.	n/a
01073000	Oyster River near Durham, NH	1934–2007	633	1,020	1,220	1,750	873	10–50	7.8	1,320	100–500	6.1	April 2007
01073460	North River above NH125 near Lee, NH (see note 1)	2004–2006	1,520	2,500	3,020	4,520	3,790	100–500	n.d.	n.d.	n.d.	n.d.	n/a
01073500	Lamprey River near Newmarket, NH	1934–2007	4,660	7,760	9,400	14,100	8,970	50–100	7.3	8,450	50–100	5.7	May 2006
01073587	Exeter River at Haigh Road near Brentwood, NH	1996–2007	3,450	6,690	8,530	14,100	3,450	10–50	n.d.	2,840	2–10	n.d.	May 2006
01073600	Dudley Brook near Exeter, NH	1962–1985	379	646	791	1,210	660	50–100	n.d.	470	10–50	n.d.	May 2006

Gage Station Number	Gage Station Name	Period of Record	Return Period Discharge (cfs)				May 2006 Flood			April 2007 Flood			Maximum Peak of Record
			10-year	50-year	100-year	500-year	Peak Flow (cfs)	Return Period (years)	Runoff (inches)	Peak Flow (cfs)	Return Period (years)	Runoff (inches)	
01073785	Winnicut River at Greenland near Portsmouth, NH (see note 1)	2002–2007	406	637	758	1,100	1,450	> 500	n.d.	1,030	100–500	n.d.	n/a
01073810	Berrys Brook at Sagamore Road near Portsmouth, NH (see note 1)	2003–2004	136	213	253	368	505	> 500	n.d.	278	100–500	n.d.	n/a
01073822	Little River at Woodland Road near Hampton, NH (see note 1)	2003–2006	202	329	395	590	774	> 500	n.d.	n.d.	n.d.	n.d.	n/a
01073838	Taylor River at Old Stage Road near Hampton, NH (see note 1)	2004	172	257	302	424	n.d.	n.d.	n.d.	436	> 500	n.d.	n.d.
01077510	Newfound River below Newfound Lake near Bristol, NH	1994–2007	2,720	3,500	3,780	4,350	3,500	10–50	n.d.	1,690	2–10	n.d.	May 2006
01082000	Contoocook River at Peterborough, NH	1946–2007	2,250	3,130	3,530	4,480	1,470	2–10	3.8	4,110	100–500	5.8	April 2007
01085000	Contoocook R near Henniker, NH	1938, 1940–1977, 1989–2007	9,240	14,300	16,800	23,900	10,400	10–50	n.d.	13,000	10–50	n.d.	September 1938
01085500	Contoocook R Below Hopkinton Dam at W Hopkinton, NH (see note 2)	1964–2007	6,070	6,880	7,150	7,630	5,460	2–10	n.d.	5,370	2–10	n.d.	April 1987
01086000	Warner River at Davisville, NH	1940–1978, 1999–2007	4,260	6,550	7,660	10,700	8,640	100–500	n.d.	6,910	50–100	n.d.	May 2006
01089000	Soucook River near Concord, NH	1952–1987	2,560	4,030	4,760	6,750	4,790	100–500	n.d.	3,500	10–50	n.d.	May 2006

Gage Station Number	Gage Station Name	Period of Record	Return Period Discharge (cfs)				May 2006 Flood			April 2007 Flood			Maximum Peak of Record
			10-year	50-year	100-year	500-year	Peak Flow (cfs)	Return Period (years)	Runoff (inches)	Peak Flow (cfs)	Return Period (years)	Runoff (inches)	
01089100	Soucook River at Pembroke Road near Concord, NH	1989–2007	2,730	4,300	5,080	7,200	5,110	100–500	6.7	3,730	10–50	4.4	May 2006
01089500	Suncook River at North Chichester, NH	1919–1920, 1922–1927, 1929–1970, 2007	5,300	9,930	12,700	21,700	7,600	10–50	n.d.	10,600	100–500	n.d.	April 2007
01090800	Piscataquog River below Everett Dam near East Weare, NH (see note 2)	1963–2007	1,580	1,910	2,010	2,220	1,540	2–10	n.d.	1,600	10–50	n.d.	June 1984
01091000	South Branch Piscataquog River near Goffstown	1941–1978	3,990	5,930	6,830	9,100	7,180	100–500	n.d.	9,700	> 500	n.d.	April 2007
01091500	Piscataquog River near Goffstown (see note 2)	1936, 1938, 1940–1978, 1983–2007	7,090	11,800	14,300	21,100	10,100	10–50	n.d.	11,200	10–50	n.d.	September 1938
01092000	Merrimack R near Goffs Falls Below Manchester, NH (see note 2)	1936–2007	52,900	86,300	105,000	163,000	74,700	10–50	6.8	59,700	10–50	4.9	March 1936
01094000	Souhegan River at Merrimack, NH	1910–1976, 1980, 1982–2007	6,370	10,400	12,600	18,800	6,140	2–10	5.3	10,500	50–100	6.2	March 1936
01141800	Mink Brook near Etna, NH	1963–1988	486	810	973	1,420	870	50–100	n.d.	n.d.	n.d.	n.d.	May 2006

Notes: (1) Some of the gages in this table have relatively short records. The peak discharge estimates for these gages with short records were computed based on regional regression equations, not statistical analysis of the gage data.

(2) Flood discharges are affected by upstream flood control works.